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LEVITATION

BY

LIGHT PRESSURE:

AN

EXPERIMENTAL THESIS

A Thesis

presented to

The Division of Mathematics and Natural Sciences

Reed College

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Arts

by

[illegible]

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A thesis
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In partial fulfillment
of the requirements for the degree
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by
Bruce D. Malamud
May 1986

Approved for the Division

Jean F Delord

Jean Delord

This thesis is dedicated to the following two sets of people:

Mommy and Daddy

and

Dr. & Mrs. McCrone

ACKNOWLEDGEMENTS

I would like to give special thanks to Jean Delord, a very patient, kind man, who helped make my senior year a very enjoyable one. Thanks to Richard DeFreez at OGC (Oregon Graduate Center) who helped me on much of my thesis and was an informal second advisor. Thanks to OGC for letting me use their equipment and lab space. Thanks to Rubie Wilson the electrical technician, Greg Eibel down in the machine shop, Nancy Bauch in the biology stockroom, and Cindy Savage in the chemistry stockroom, all of whom helped me to find and make the objects that I desired for my thesis and everything else I needed during the last couple of years at Reed College. Final thanks go to my proof readers, Nada, Nic, and Alex, and to all my friends at Reed.

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ABSTRACT

The forces exerted by a focused laser beam are enough to levitate and optically trap small dielectric spheres. In this thesis, various aspects of light pressure are investigated. A 200mW Argon laser is used to stably trap diffusion pump oil droplets in the 1-10μ (radius) range. A 1.5W YAG laser and 200mW Argon laser are then used to levitate spheres of dye-doped polyethylene glycol. Fluorescence and possible lasing action occurred.

PREFACE

Light has always fascinated me. One of the reasons that physics is so enjoyable for me is because of all the possibilities of optics and the visual understanding that comes with it. During my junior year, as part of a junior lab project on lasers, I came across a reference in Jearl Walker's Flying Circus of Physics on levitation by light pressure. I had of course seen the result of forces due to gravity, electrostatics, heat, etc., but had never realized that the force due to light pressure was strong enough to be observed.

Since reading Jearl Walker's comment on light pressure, the idea of actually using light to physically lift a small object and suspend it in midair has held my keen interest. It is amazing to see light hit an object and hold it in place without any other external forces. More amazing, is the fact that one can use this force to trap an object, move it around, and perform experiments on it.

The main goal of this thesis was to have fun. Another goal was to learn more about different aspects of experimental physics in optics, particularly with lasers. The topic I picked definitely had something to do with the success of these goals. This was a fun and an educational thesis. Much of the time was just playing around, but happily enough, that is what physics should be. I hope that in the write up of this thesis I can convey, if only partly, some of the fun and excitement I had levitating a little sphere of liquid and optically trapping it.

CHAPTER I

HISTORY OF LIGHT PRESSURE[1]

INTRODUCTION

This chapter gives an overview of the history of light pressure. The chapter starts with a discussion of the effects of light pressure on comets, since it is comets that first drew the attention of people to light pressure, and because the back of the envelope calculation of the forces involved is easy.

Then, the chapter presents a discussion of a failed experiment to detect light pressure, Crookes' Radiometer. This experiment is discussed because it gives an idea of how small the forces due to light pressure are, and some of the factors against which light pressure is battling. More important, Crookes' Radiometer is a stepping stone for an experiment that did achieve a detection of light pressure, which is then discussed.

EFFECTS OF LIGHT PRESSURE ON COMETS

Comets have always fascinated people, and it was from this fascination that the first theories on light pressure emerged. As early as 1531, Peter Apian, also known as Petrus Apianus (1495-1552), a well known geographer of the sixteenth century, noted the fact that the tails of comets point away from the sun.[2] Then, in 1619, Johannes Kepler (1571-1630) postulated that the

pressure of light was the reason that comets' tails always point away from the sun.

There are many interesting quotations that one can find about comets and light pressure. The following dates from the turn of the century (1905), and was given by John H. Poynting (1852-1914) in his presidential address to the Physical Society. (Note that light pressure and radiation pressure are used pretty much interchangedly).

> There is one more effect of this radiation pressure which is worthy of note: its sorting action on dust particles. If the particles in a dust cloud circling round the sun are of different sizes or densities, the radiation accelerations on them will differ. The larger particles will be less affected than the smaller, will travel faster round a given orbit, and will draw more slowly in towards the sun. Thus a comet of particles of mixed sizes will gradually be degraded from a compact cloud into a diffused trail lengthening and broadening, the finer dust on the inner and the coarser on the outer edge.[3]

In this quotation, Poynting gives the correct concept that light pressure causes comets to have a tail, however, he talks about the "fine dust going to the inner and the coarser to the outer edge." In actuality, the fine dust is pushed to the far end of the comet tail, far away from the sun, and the coarser dust is towards the head of the comet, closer to the sun. He also makes the puzzling statement that the large particles will draw more slowly into the sun than the small particles.

In a more modern source (Essentials of Astronomy by Motz and

Duveen, 1966) we find a very good discussion and calculation of the effect that radiation pressure has on comet tails.[4] There are two comet tails, the plasma tail, which consists of a stream of ionized hydrogen that one cannot see, and the dust tail, composed of many small particles. It is the dust tail that one sees when looking at comets with the eye. The plasma tail is affected by the solar wind (a steady stream of charged particles flowing away from the sun) and by magnetic fields from the sun, and the dust tail is affected mostly by radiation pressure.

The repelling force from the sun due to radiation pressure can be calculated to be 30-100 times the attracting force of the sun's gravity when talking about the small particles ($<2.5\times10^{-6}$ cm) of the comet's tail. When comparing the force of radiation to the force of gravitation on a single particle in the comet tail (as worked out in Motz and Duveen) one finds that

$$\frac{\text{force of radiation}}{\text{force of gravity}} = \frac{\dfrac{Lr^2}{4\,cd^2}}{\dfrac{\frac{4}{3}\pi GM\rho r^3}{d^2}}$$

$$= \frac{L}{\frac{4}{3}\pi GMc}\left(\frac{1}{\rho}\right)\left(\frac{1}{r}\right) \qquad (1.1)$$

where;

$L \equiv$ total luminosity of the sun $= 4 \times 10^{33}$ ergs/sec $= 4 \times 10^{26}$ Nm/sec
$G \equiv$ gravitational constant $= 6.7 \times 10^{-11}$ Nm^2/kg^2
$M \equiv$ mass of the sun $= 2 \times 10^{30}$ kg
$c \equiv$ speed of light $= 3 \times 10^{8}$ m/sec
$\rho \equiv$ density of the particle $=$ 3 gm/cc for average rock $=$ 3000 kg/m^3
$r \equiv$ radius of that particle (in m)
$d \equiv$ distance of particle from sun (drops out of the equation)

From (1.1) it can be seen that the smaller the particle, the greater the repulsive force of radiation with respect to the attractive force of gravity, causing a greater net force on the particle pushing it away from the sun. Substitution of all of the average values given (working in mks units) yields (force of radiation / force of gravity) $\approx (2 \times 10^{-7}$ m$) \times (1/r)$. This means that those particles bigger than about 0.2μ will fall towards the sun (i.e. the force of gravity is bigger than the force due to radiation pressure) and those smaller then 1μ will be pushed away from the sun, causing the comet to form a tail.

The smaller the particle, the farther it will be pushed away from the sun, eventually being pushed out of this solar system. This gives us some insight into why the tail of the comet points away from the sun. The smallest particles are pushed away with more force than the larger particles, causing the smaller particles to go further away from the sun. There are other forces at work here, not just gravity and radiation pressure, so this previous discussion is a somewhat simplified version of how comet tails are effected by radiation pressure.

CORPUSCULAR THEORY OF LIGHT

In 1665, Isaac Newton (1642-1727) began thinking about his corpuscular (sometimes called emission) theory of light, which he published in 1675. In this theory, light could be viewed as a stream of particles. A luminous body would emit small elastic particles that traveled with the speed of light. This theory helped explain the interaction of light with matter, and made the idea of radiation pressure more plausible. With the help of this theory, one could imagine a particle coming from a light source, travelling with the speed of light, and having some momentum that it could impart to what ever object it hit. With this theory, one could predict that if a photon were reflected by an object, it would impart twice as much momentum as if it were completely absorbed by that object. Newton's corpuscular theory stimulated many experimental attempts to actually measure light pressure.

During the eighteenth and nineteenth centuries, all attempts to measure light pressure failed. They failed to reveal forces other than that which could be attributed to convection in the air caused by heat (radiometric forces). The experiment that is most remembered today, is that of Crookes' Radiometer.

CROOKES' RADIOMETER

In 1873, Sir William Crookes (1832-1919) built what is now called Crookes' Radiometer (also called a light windmill or solar radiometer). Crookes' Radiometer (see Fig. 1.1) consists of a set of four wings that are

attached to a small piece of glass (a vane, like a weather vane) which rests on a needle. The vane and needle are enclosed in a bulb shaped piece of glass that has been evacuated. The wings of the vane are shiny (white) on one side and dull (black) on the other.

Crookes thought, using the Corpuscular theory of Newton, that when a strong enough light was shined on these wings, the vane should rotate with the shiny sides of the wings trailing. In other words, he thought that the photons hitting the shiny or white side should impart twice as much momentum as the photons hitting the dull or black side, thus causing a rotation with the black sides leading.

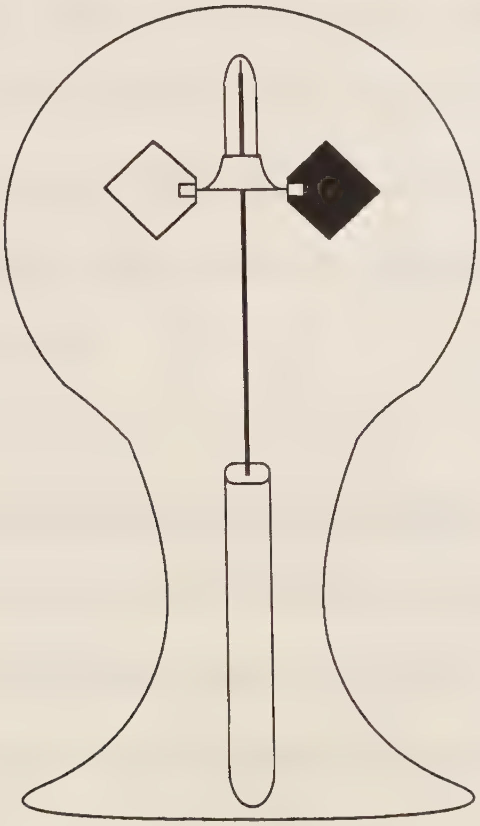


Figure 1.1 Crookes' Radiometer

In fact, when Crookes tried the experiment the exact opposite happened, the white (shiny) sides led, and the black (dull) sides trailed. This can be understood from the fact that although there is a partial vacuum inside the bulb, there is still some gas in it. The kinetic theory of gases predicts that there will be a larger recoil of residual gas molecules from the hot black surface than from the cooler white shiny surface. The black surface absorbs more of the light than the white surfaces, causing the temperature and therefore the pressure on the black surface to be greater than on the white surfaces, and this causes the vane to turn with the white surfaces leading. (See the next section for a round-figure calculation of the gas pressure.) It has been observed that the vane can revolve up to speeds of about 3000 revolutions per minute.[5]

To be positive that light pressure is only having a miniscule effect in this experiment, one could reduce the vacuum in the bulb to the point where there are very few molecules to heat up. What one would find is that the vane will stop turning altogether because of the friction of the glass against the metal needle, and the weight of the vane.

PREDICTING EXACT MAGNITUDE OF RADIATION PRESSURE

In 1873, James Clerk Maxwell (1831-1879) predicted the magnitude of radiation pressure based on his new theory of E & M waves. From these predictions, he was able to say that for ordinary light sources, the pressures would be very small.

As an example, consider Crookes' Radiometer. According to Maxwell, the radiation pressure is the intensity over the speed of light if the photons are absorbed (P_r = I/c), and twice this if the photons are reflected (P_r = 2I/c). In the case of Crookes' Radiometer, assume that the photons are completely reflected by the white side, and completely absorbed by the black side. Then there exists a net pressure of ((2I/c) - (I/c)) due to radiation pressure giving

$$\Delta P_r = \frac{I}{c} \tag{1.2}$$

Assume that the intensity of light hitting the wings of the vane in Crookes' Radiometer is on the order of 100 W/m^2 (the intensity of a bright light bulb). Then ΔP_r is approximately 3×10^{-7} Pa.

Now consider the ΔP due to gas pressure. For the sake of simplicity, assume that the white side of each wing stays at ambient temperature, call it T_w for the temperature of the white side (it is also the temperature of the air). Also, assume that the black side of each wing heats up to some temperature, call it T_b for the temperature of the black side. The molecules that hit the white side will impinge with a temperature T_w (the temperature of the container)--or more correctly with a normal momentum P_x such that $\{\langle P_x{}^2\rangle / 2m\} = \{kT_w / 2\}$, and will leave with a temperature T_w (the temperature of the white surface is the same as the temperature of the air). The molecules that hit the black side will impinge

with a temperature T_w (container temperature) and will leave with a temperature T_b, the temperature of the black side. So, the molecules that hit the black side will have an average temperature of $((T_b + T_w) / 2)$, which means that $k\Delta T$ is the difference in average energy of the molecules off the black and white sides, with ΔT having the simple expression:

$$\begin{aligned}\Delta T &= ((T_b + T_w) / 2) - T_w \\ &= ((T_b - T_w) / 2)\end{aligned}$$

The pressure difference due to this difference in temperature can be calculated using the ideal gas law $PV = nRT$:

$$\Delta P = \frac{nR\Delta T}{V} \qquad (1.3)$$

The atmospheric pressure is then given by:

$$P_{atm} = \frac{n_o R T_o}{V} = 1 \times 10^5 \text{ Pa} \qquad (1.4)$$

In (1.4) T_o is just ambient temperature, T_w. In addition, (n_o/V) is the number of moles per unit volume (where V is some unit volume). The Crookes' Radiometer has a vacuum of about 10^{-6} atm., compared with normal atmospheric pressure which is about 1 atm. This $n = n_o \times 10^{-6}$. Dividing (1.3)

by (1.4) and putting in substitutions, yields

$$\frac{\Delta P}{P_{atm}} = \frac{\dfrac{n_o \times 10^{-6} R \Delta T}{V}}{\dfrac{n_o R T_w}{V}} = 10^{-6} \frac{\Delta T}{T_w} \qquad (1.5)$$

Taking ΔT to be about 5 K (this assumes that the black side is 10 degrees hotter than the white side), T_w to be about 300 K, and $P_{atm} = 10^5$ Pa, and substituting into the R.H.S. of (1.5), yields $\Delta P = 1.5 \times 10^{-3}$ Pa. This is a net pressure that is four orders of magnitude greater than that due to radiation pressure, $\Delta P_r = 3 \times 10^{-7}$ Pa. This brief calculation of radiation pressure vs. gas pressure (the gas pressure resulting from radiometric forces) shows how very small radiation pressure is.

EXPERIMENTAL SUCCESS

In 1901, Edward Leamington Nichols (1854-1937) & Gordon Ferrie Hull (1870-1956) in the U.S., and Pytor Nikolaievich Lebedev (1866-1912) in Russia, both demonstrated the existence of radiation pressure free from thermal effects.[6] In both experiments the radiation pressure exerted by a powerful light source was detected by a twisting motion of a vane suspended by a fine fiber in a high vacuum. This is similar to Crookes' Radiometer, except that there was a very fine vacuum, very little friction involved, and the vane was composed of

special cells so that any radiometric forces in the cells produced no net force. The forces detected by each team agreed with Maxwell's predictions within one percent.

A good film of a similar experiment was made by J.R. Zacharias of MIT in 1958.[7] In the experiment, a 20W lamp is used to push a very thin piece of aluminum foil (vane) which is hung from a 2 foot length of a very thin fused quartz fiber. The quartz fiber is attached at the top, and everything is contained in a glass apparatus which is reduced to 10^{-11} atmospheres. The lamp is shined periodically off and on the vane, creating a resonance effect (like someone pushing a swing), enhancing the effect of seeing the vane start to swing.

In this experiment, the possibility that other forces were causing the vane to start moving, was ruled out because these other forces were very small compared to the force due to radiation pressure--the advantage of working in a vacuum.

Indeed, it can be shown that the radiometric forces at 10^{-11} atm. are two orders of magnitude smaller than the force due to radiation pressure, showing that it is light pressure that is demonstrated in the experiment.

An interesting thesis project (or ambitious junior lab project) would be to repeat the basic idea of this experiment, using a high vacuum, a spider web in place of the quartz, and a laser for the light source.

THE INSIGNIFICANCE OF LIGHT PRESSURE

As part of the closing remarks of his presidential address to the Physical Society, Poynting said, "A very short experience in attempting to measure these light-forces is sufficient to make one realise their extreme minuteness--a minuteness which appears to put them beyond consideration in terrestrial affairs."[3] It is apparent from the various physics journals published around the turn of the century, that the idea that radiation pressure would never be useful was quite widespread. It was not until 1960 that this changed.

THE LAST 25 YEARS

In 1960 the laser was invented. This put a new light (just a little levity) on the use of radiation pressure in terrestrial affairs. With the laser came a source of light that can be tightly focused, is coherent, does not diverge much, and is much more powerful then anything existing before.

In 1970, Arthur Ashkin (Bell Labs) published a paper in Physical Review Letters in which he described the use of light pressure from a laser beam to push around, manipulate, and optically trap, micron sized transparent latex spheres in water.[8] In addition, in this paper, he discussed 5μ-diam spheres of water that were created by means of an atomizer, fell down through the air, and were then trapped and accelerated upwards in the beam of a 50mW laser.

Then, in 1971, Ashkin presented a paper in Applied Physics Letters discussing levitation by light pressure.[9] In this paper, he described levitating,

manipulating, and optically trapping a transparent glass sphere 20µ in diameter, in air, with a vertical 250mW green laser beam. Ashkin showed that precise manipulation of micron size particles suspended in air by light pressure could be achieved.

In 1972, Ashkin presented a paper in Scientific American, in which he discusses his results from the previous two years.[10] In the paper, he explains levitation, then goes on to present a few applications, such as looking at the forward Mie scattering to calculate the exact diameter of the sphere he was using. Mie scattering is named after Gustav Mie (1868 - 1957) who in 1908 published a paper dealing with the problem of scattering of light by spherical objects. Being able to see Mie scattering, free of outside disturbances, would be very useful if one had a sphere made of some viscous solution that was slowly evaporating. One could then measure easily, using Mie scattering, how fast the diameter of the sphere was changing.

Since then, Ashkin and others have gone on to show that levitation with light pressure can be used with particles ranging from micron size down to molecules and atoms. Small particles can be stably trapped in air[9,11,12], liquid[8], or vacuum[13,14] and it is then possible to

- -separate some types of particles from others[15]
- -levitate them against gravity
- -manipulate them singly
- -combine them in pairs[16]

- channel them along laser beams and use them as probes to measure
    - Optical forces[17]
    - Electromagnitism forces[18,19]
    - Radiometric forces
    - Viscous drag forces
    - Gravity forces
    - etc.

These techniques have applications to

- light scattering / Mie scattering[17]
- atmospheric physics[12]
- aerosol science
- planetary physics
- laser fusion[11,14]
- atomic and molecular physics[20-23]

Radiation pressure can be used to explain many phenomena and to perform many experiments. In some stars, radiation pressure is the force that pushes out to keep the star from collapsing due to gravity. In futuristic spaceships, light pressure is used as the drive to accelerate the spaceships. In biology, light pressure can be used to separate some types of cells from others. Light pressure, and in particular, levitation by light pressure, is a tool that has

been used by many scientists over the last decade and a half. Virtually, every month there are new articles published using radiation pressure as a tool to do some experiment or another. It is amazing that something so small, that involves so little pressure, can now be so useful.

CHAPTER II

THEORY

INTRODUCTION

This chapter explains some of the theory involved with radiation pressure. In experimental work for this thesis, mostly transparent, dielectric (nonconducting) spheres have been used. One could use reflective spheres (highly reflective metal particles), but even with 98 percent reflectivity, the absorption of 2 percent of the light could cause melting of the metal when lasers are used to lift the metal sphere.[1] Of course, it might be interesting to calculate the forces on, and try to optically lift the metal particles once they have been melted. However, as described here, transparent dielectric spheres have been used to alleviate problems arising from thermal (possible melting) and radiometric forces.

There are (among others) two different approaches to levitating dielectric spheres. The first would involve using small, spherical, transparent polystyrene or glass spheres that one can purchase from various commercial sources.[2] These glass and polystyrene beads are highly resistant to heat build up. The polystyrene spheres (whose density is about the same as water) could then be put in a solution of water (or alcohol), pushed out by an atomizer, then caught by a vertical laser beam as they are falling. Alternatively, (as Ashkin has done), one can put the glass bead on a glass surface, then use a piezoelectric

ceramic cylinder to shake the glass bead loose of the Van der Waals force (forces of molecular attraction that make small particles stick to any surface), and use a laser to push the glass bead up off the glass surface and levitate it with light pressure.

Secondly, as is done in the experiments described in this thesis, one can take a liquid that has a low vapor pressure, is transparent, will not pick up charge easily, and create small spheres from the liquid with an atomizer. A cascade of different size spheres falling down due to gravity can then be caught by a vertical laser beam and levitated by light pressure.

A few simple calculations involving radiation pressure are now presented as a precursor to a short discussion of the lifting and lateral restoring forces on an optically levitated sphere.

"BACK OF THE ENVELOPE" CALCULATIONS

Following are two examples, one of radiation pressure from a lightbulb, the other from the sun.

The radiation pressure at a distance of 3m from a 100W bulb, assuming 50W goes into electromagnetic radiation, is calculated first.

The intensity is average power per unit area, so at 3m, 50W going through a sphere of radius 3m, gives:

$$I = \frac{P_{av}}{4\pi r^2} = \frac{50W}{4\pi(3m)^2} = 0.44\ W/m^2 \qquad (2.1)$$

In the case of normal incidence and complete absorption of the incoming light, the radiation pressure is the intensity divided by the speed of light, (for total reflection of the incoming light, the radiation pressure is twice this quantity), so

$$P_r = \frac{I}{c} = \frac{0.44\ \mathrm{W/m^2}}{(3 \times 10^8\ \mathrm{m/sec})} = 1.5 \times 10^{-9}\ \mathrm{Pa} \tag{2.2}$$

This is a very small pressure compared with atmospheric pressure which is on the order of 10^5 Pa.

The intensity of sunlight hitting the earth is about 1300 W/m^2. (We will ignore clouds and pollution.) If the sunlight is totaly absorbed, the radiation pressure on the earth is just

$$P_r = \frac{I}{c} = \frac{(1300\ \mathrm{W/m^2})}{(3 \times 10^8\ \mathrm{m/sec})} = 4.3 \times 10^{-6}\ \mathrm{Pa} \tag{2.3}$$

Again, this is a very small pressure compared with that of atmospheric pressure (about 10^5 Pa). Converting from SI units to English units, we can see that 4.3×10^{-6} Pa ~ 1 lb/mile^2.

The purpose of these last two calculations is to show how easily a rough estimate of light pressure on a surface can be calculated, and how small the numbers actually are. It is true that light pressure is a very small force when

compared to other forces, but when using the laser, it can be a significant force indeed. In addition, on large objects, forces like gravity will always be large compared to light pressure. The force of gravity is dependent on r^3, whereas the force due to light pressure has a dependence on r^2, meaning that when objects get smaller, forces such as gravity decrease faster then forces such as radiation pressure.

Another similar calculation can be done by substituting a laser as the source of light. Assume that a 10mW, 1mm radius, laser beam hits an object and is totaly absorbed, the radiation pressure exerted on that object is

$$P_r = \frac{\frac{\text{Power}}{\text{unit area}}}{c} = \frac{\frac{10\text{mW}}{\pi(1\text{mm})^2}}{(3 \times 10^8 \text{ m/sec})} = 1.1 \times 10^{-5} \text{ Pa} \tag{2.4}$$

If this laser beam were to be focused down to a 1μ radius, and the power increased to a moderately powerful 1W, then the radiation pressure at the focus point of the laser beam on an object that absorbs the light would be about 1.1×10^3 Pa, a number far greater than anything attained with the sun.

If such a beam was focussed on a dielectric sphere of radius 1μ, density 1 gm/cc, and reflectance R = 0.1 (the amount of light reflected back). The radiation pressure would be

$$P_r = \frac{2RI}{c} = \frac{(2)(0.1)(3.2 \times 10^{11} \text{ W/m}^2)}{(3 \times 10^8 \text{ m/sec})} = 2.1 \times 10^2 \text{ Pa} \tag{2.5}$$

The force due to radiation pressure on this sphere would be

$$F_r = \frac{2RP}{c} = \frac{(2)(0.1)(1W)}{(3 \times 10^{8}\ \text{m/sec})} = 6.7 \times 10^{-10}\ \text{N} \tag{2.6}$$

And, the acceleration of this sphere would be the force divided by the mass or

$$a = \frac{F_r}{m} = \frac{F_r}{V\rho} = \frac{6.7 \times 10^{-10}\ \text{Kg m/sec}^2}{(\frac{4}{3}\pi(1 \times 10^{-4}\ \text{cm})^3)(1\ \text{gm/cm}^3)} = 1.7 \times 10^{5}\ \text{m/sec}^2 \tag{2.7}$$

This gives an amazing "back of the envelope" result of an acceleration due to light pressure of a small dielectric sphere that is 20,000 times the acceleration of gravity.

Of course there are many forces which can be orders of magnitude greater then the forces due to radiation pressure, such as air currents, viscosity, electrostatics, photophoresis effects (uneven heating of the sphere), thermal effects (such as melting the sphere), etc. The photophoresis, thermal, and electrostatics effects can be dealt with by using small transparent dielectric spheres. The air currents (if using air as the medium in which the spheres are to be levitated) can be avoided by using a self enclosed system where air cannot leave or enter easily, and where the design of the system does not promote unnatural air currents.

FORCES ON A SPHERE

Now, consider some of the forces involved with levitating and trapping a sphere with a laser beam. The laser beam will be in the TEM_{00} mode. TEM stands for Transverse ElectroMagnetic, where the light waves consist of electromagnetic fields that are transverse to the direction of propagation. In the TEM_{00} mode, a ray travels back and forth along the axis. The output of a laser oscillating in the TEM_{00} mode is a spherical wave with a Gaussian intensity distribution. The sphere we are dealing with will have a diameter that is smaller than the beam width of the laser beam. Place the sphere off-axis, on one side or the other of the vertical TEM_{00} mode Gaussian beam (see Fig. 2.1).

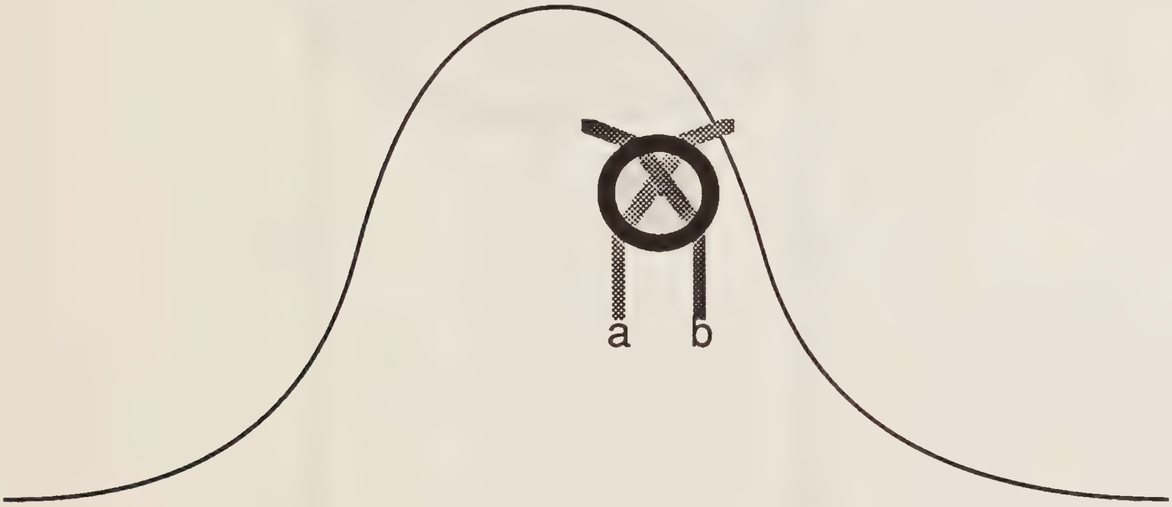


Figure 2.1 Gaussian laser beam intensity with sphere off axis

If the refractive index of the sphere is greater than that of the medium, and two rays of light, **a** and **b**, refract through the sphere, then the two forces

that result are F_a and F_b (see Fig. 2.2). These two forces are in the direction of the momentum change and are the chief components of the total force due to the laser beam (assume that surface reflections are negligible).

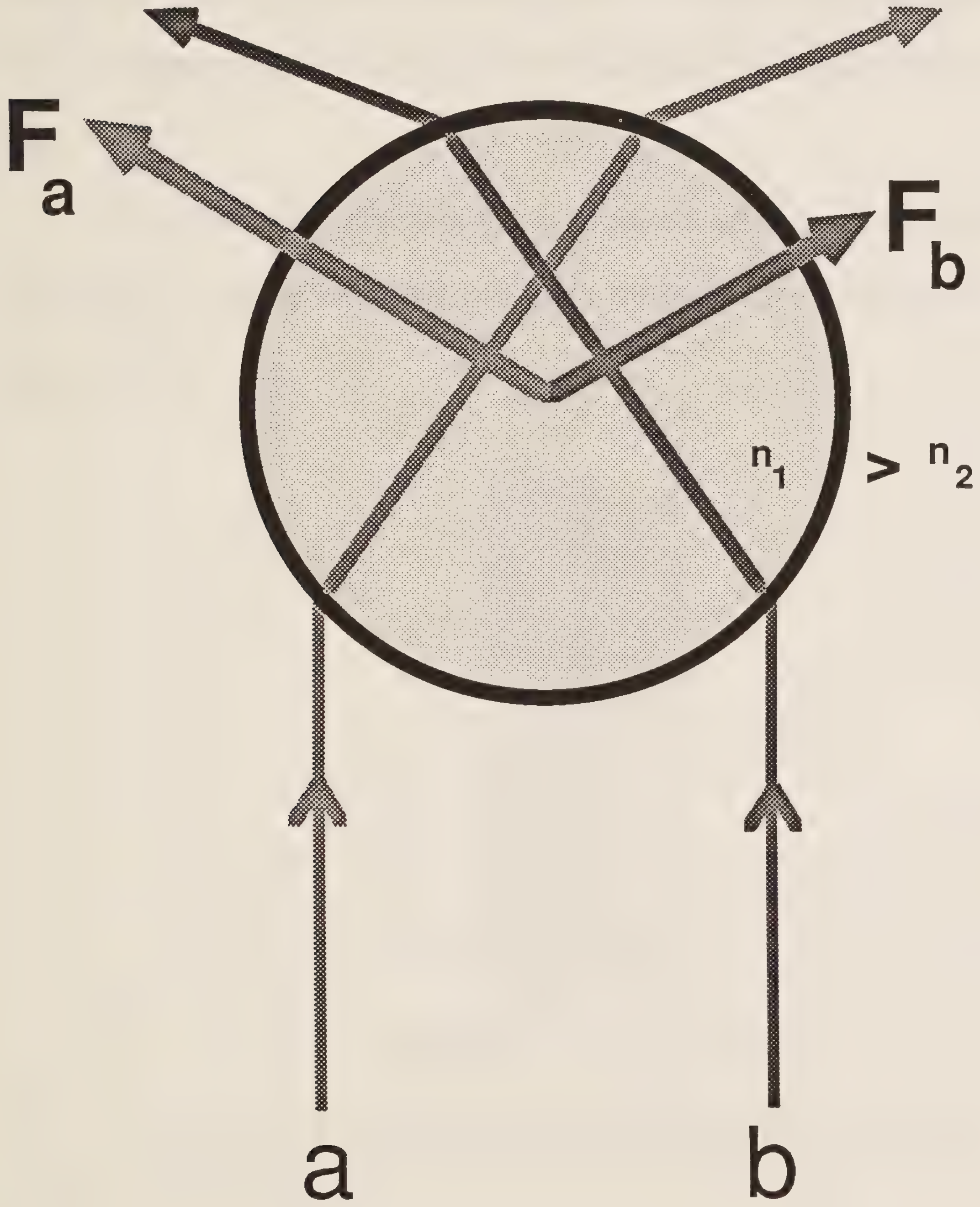


Figure 2.2 Forces on a sphere

If the light ray from **a** is more intense than that of **b**, then $F_a > F_b$. The intensity of the light rays depends upon where they are with respect to the axis of the beam. There are two components to the net force, the vertical force which is directed up, giving the lifting power of light pressure, and the horizontal force, directed towards the area in the laser beam of highest intensity, the beam axis.

This horizontal gradient force causes a sphere that is off axis, on one side or the other of the laser beam, to be pulled into the center of the laser beam (see Fig. 2.3).

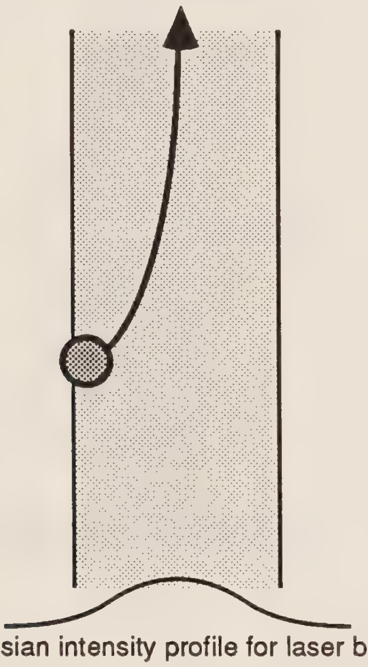


Figure 2.3 Particle goes towards center of the beam

If the laser beam is focused by use of a lens, the Gaussian intensity profile will not be lost, the maximum intensity will still be found on the beam

axis. A sphere will be drawn into the center of the laser beam, and will stabilize at a point above the focus of the laser beam where the intensity of the laser beam is such that the force due to light pressure in the z direction (up), is equal to the force due to gravity (down). Assume that at this point the sphere has no velocity, causing the viscous force to be 0. This gives an optical trap (see Fig. 2.4).

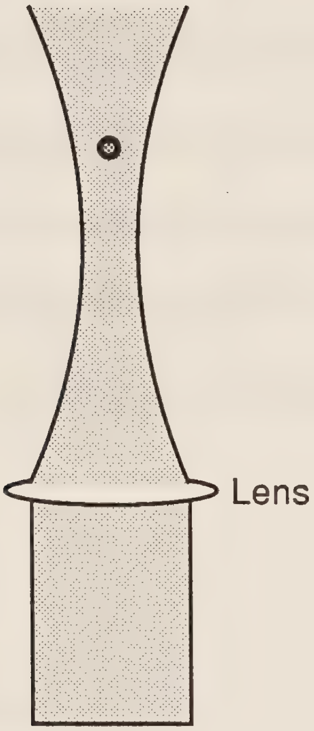


Figure 2.4 Optical trap

The general problem of levitation and trapping of a small dielectric sphere in a polarized diverging laser beam having a Gaussian profile is admittedly a difficult one. A recent paper by Kim and Lee gives a complete account of the forces involved for a sphere in a diverging laser beam with a Gaussian profile.[3] The result requires a complicated summation and a detailed

knowledge of the beam parameters.

Our own efforts in this direction convinced us that a general solution was beyond the scope of this thesis, and we made the choice to rely on simple arguments and "back of the envelope" calculations.

CALCULATING SIZE OF A DROPLET

In the experiments described in the next two chapters, drops that are created from an atomizer fall down a glass tube which has cm markings on the side of it. If one knows the speed of the droplets, and pertinent data about the liquid used, then one can figure out quite easily the size of the droplets.

For this, Stokes' Law (2.8), which says that a fluid with nonzero viscosity exerts a drag force (F_S) on a moving spherical particle can be used:

$$F_S = 6\pi\eta r v \tag{2.8}$$

where;

$\eta \equiv$ viscosity of medium
$= 183\ \mu$poise for air at 25° C
$r \equiv$ radius of the sphere
$v \equiv$ velocity of the sphere.

If the sphere is falling through air, then the force of gravity is acting downward, and Stokes' force plus the buoyant force of air displaced by the droplet are acting up, giving expression (2.9). The velocity of the sphere, as it is falling through the air will very quickly achieve its terminal velocity (v_T).

$$F_g = (\text{mass of air displaced by droplet})g + F_S \qquad (2.9)$$

(2.9) gives

$$(4/3)\pi r^3\rho g = (4/3)\pi r^3\rho' g + 6\pi\eta r v_T \qquad (2.10)$$

where;

$v_T \equiv$ terminal velocity
$g = 9.8$ m / sec^2
$\rho \equiv$ volume mass density of sphere
$= 1.09$ gm / cm^3 for Dow Corning 705 high vacuum oil
$= 1.128$ for Carbowax (Polyethylene Glycol) 400 at 20° C
$\rho' \equiv$ volume mass density of fluid
$= 0.001$ gm / cc for dry air.

Since $\rho \ll \rho'$, (2.10) reduces to

$$(4/3)\pi r^3\rho g = 6\pi\eta r v_T \qquad (2.11)$$

Solving for r in (2.11) yields

$$r = \sqrt{\frac{9\, v_T\eta}{2\, g\rho}} \qquad (2.12)$$

Substitution of numerical values for η, g, and ρ, gives the two equations

$$r\,(\text{in } \mu) = \sqrt{V_T\,(\text{in cm / sec})} \times 8.8 \qquad (\text{Dow Corning 705}) \qquad (2.13)$$

$$r\,(\text{in } \mu) = \sqrt{V_T\,(\text{in cm / sec})} \times 8.6 \qquad (\text{Carbowax 400}) \qquad (2.14)$$

This presents an easy way to measure the radius of a droplet by timing how fast it falls.

CHAPTER III

EXPERIMENTAL SETUP

INTRODUCTION

This chapter discusses the basic experimental setup. Before doing so, however, some of the forces acting against radiation pressure must be further explored so that the reader may better understand why this particular setup was chosen.

Photophoresis effects are of course one problem to be dealt with by any optical levitation experiment.

> Photophoresis is the force on a particle due to the rebounding of ambient gas molecules with greater velocities from parts of the surface which are at a higher temperature. Absorbing nonspherical particles driven by such a force are known to migrate along complex paths. The motion can be along helical paths, complex orbits, or just irregular random movement. For all of these paths, with the exception of the random motion, there is always a preferred direction, e.g., the axis of the orbit, due to some external factor such as the direction of the light, gravity, and applied electric and magnetic fields.[1]

Recent studies have shown that these photophoretic forces can be used, when carefully calculated, to stably trap and capture absorbing particles.[1,2] For the purposes of this thesis, however, the photophoretic forces

are a destabilizing influence on the forces due to radiation pressure and gravity.

Air currents are another major problem. Viscous forces (including those due to air currents) are proportional to r (radius of the liquid drop), whereas the forces due to radiation pressure are proportional to r^2. The larger the droplet, the less it is affected by air currents. A very tiny air current can take a small droplet and destabilize it even after it has been optically trapped. This, then, provides incentive for isolation of the levitation region from outside air currents.

In addition to air currents due to the presence of small holes in the setup, the laser beam itself heats the gas and provides the energy for air movement. A larger box is more likely to allow air currents than a cylinder of small diameter. As an example, in one of the first setups, liquid dielectric spheres were dropped from the top of a glass tube, using an atomizer, and proceeded to smoothly fall through the large glass tube. About two-thirds of the way down, however, they stopped, and headed up again, because of a little air current.

Another problem initially encountered was vibration. If a droplet is stably levitated, and something hits the setup (or touches it) this could jar the apparatus, displace a mirror or a lens, or create unwanted air currents, causing the oil droplet to destabilize.

All of these problems and others will be mentioned in the following description of the experimental setup.

BASIC SETUP

Fig. 3.1 shows a scaled down version of the basic setup. At the bottom of the tube is a rubber stopper (or a rubber cork) with a hole to allow passage of the laser beam and a square glass coverslip cemented onto it. At the top of the tube is a square plastic box which is a small reservoir of air for the oil droplets to collect in after being shot out by the atomizer and before beginning their descent down the tube.

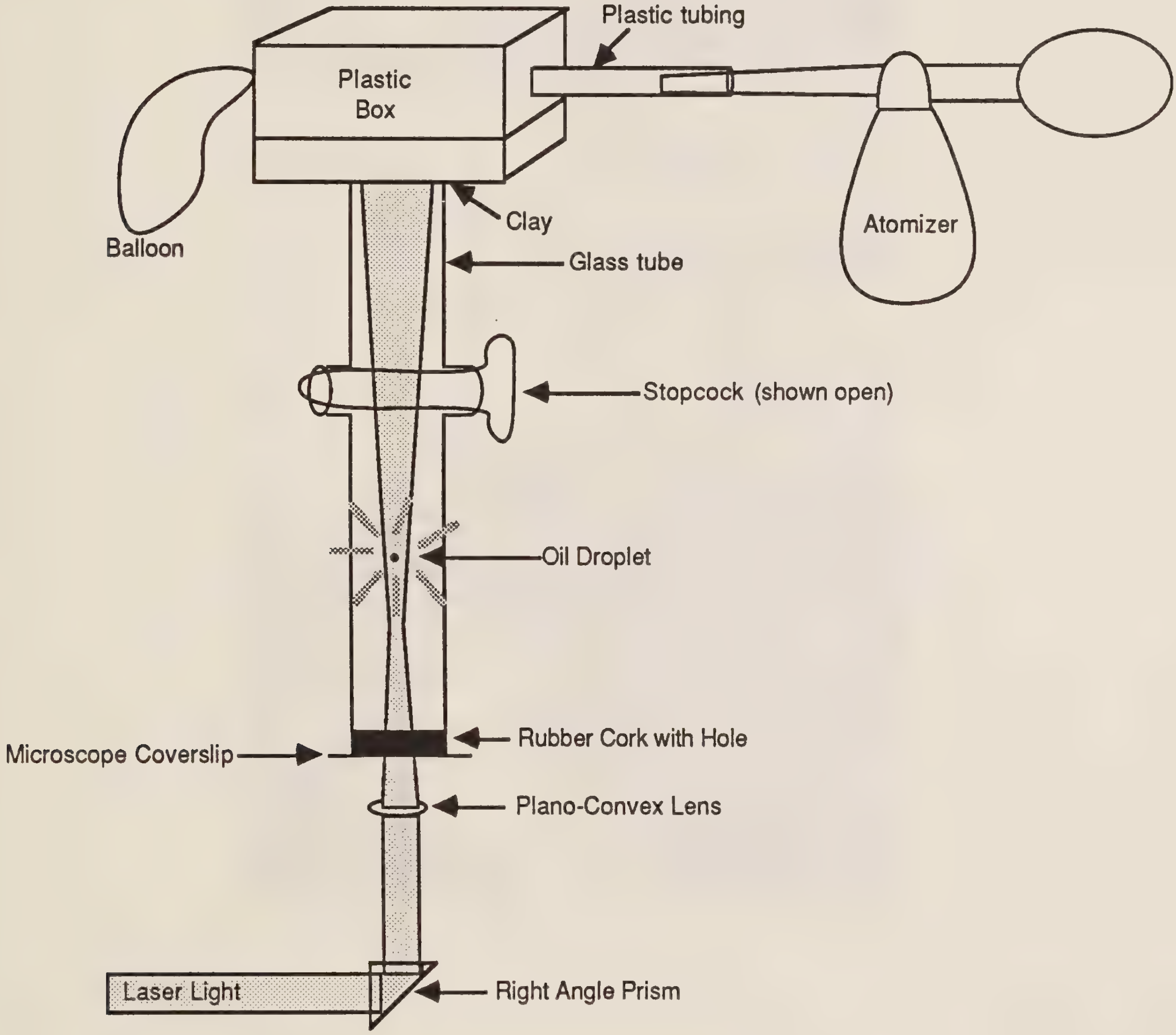
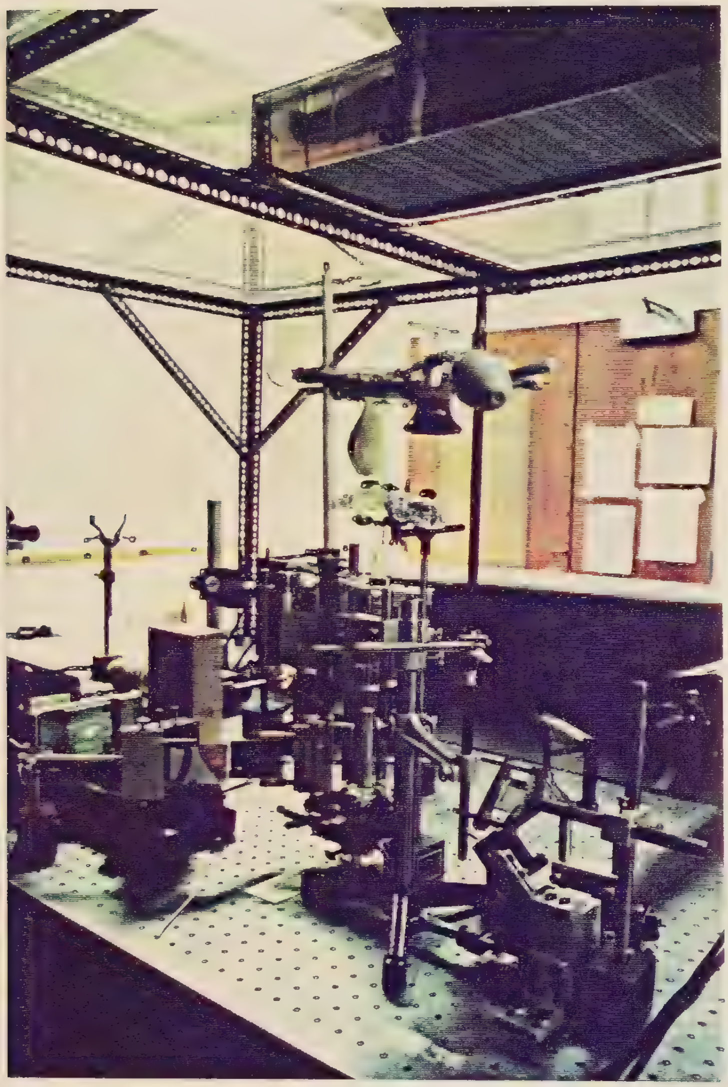


Figure 3.1 Basic Setup

The tube has a stopcock in it, so that when oil droplets drop through the tube, the flow can be easily stopped. The laser beam is turned from horizontal to vertical with a 90 degree prism, and focused by a lens to a point about 2cm above the bottom of the tube.

See Picture 3.1 for the setup as it was in the lab.



Picture 3.1 Experimental setup

The trapping procedure for a falling drop is as follows. The laser beam can be adjusted by means of an x-y translation stage, making micromanipulation of the beam easy. While the oil droplets fall, one droplet is captured with the laser beam by placing the beam focus directly under a drop using the x-y stage. The stopcock is then shut so that no more oil droplets can enter the lower half of the tube.

The whole setup, as described in this chapter, is very easy to move and to take apart. Each piece is held in place by a clamp, and everything is connected to a main stand. Objects like the telescope and x-y translation stage are on a stand of their own, attached by magnetic stands to the optical table used in the experiments.

OIL USED TO CREATE DROPS

The oil used for the droplets in the experiments presented in chapter 4 was Dow Corning® 705 Diffusion Pump Fluid, which is a silicone based fluid. This oil is normally used in ultrahigh vacuum diffusion pumps because it has a low vapor pressure and a high thermal stability. The oil has a kinematic viscosity at 25 C of 175 centistokes, and a specific gravity (density) at 25 C of 1.09 gm/cc. Kinematic viscosity is defined as the ratio of viscosity to density. The viscosity is quite important, because oils or other liquids with a very high viscosity make it difficult to generate droplets with the atomizer. The refractive index is approximately 1.5. More information is available in publications from Dow Corning.[3]

Chapter 5 discusses the use of polyethylene glycol with dye dissolved in it to create droplets. Carbowax 400 is another name for polyethylene glycol with a molecular weight of 400. There are of course other liquids (water, glycerol, pancake syrup, etc.) that one can use. Many of these will evaporate once they have been caught by the laser beam. This is interesting to watch, since as the liquid drops evaporate their diameters get smaller and they move farther away from the focus of the laser beam.[4] However, for the few experiments done in this thesis, it was desirable to have a liquid that would be fairly stable and be able to handle the high optical intensity of the laser beam without photophoresis effects masking the effects due to light pressure.

ATOMIZER

It took two weeks to find an atomizer (see Fig. 3.2) that gave oil drops in the size range appropriate for optical levitation.

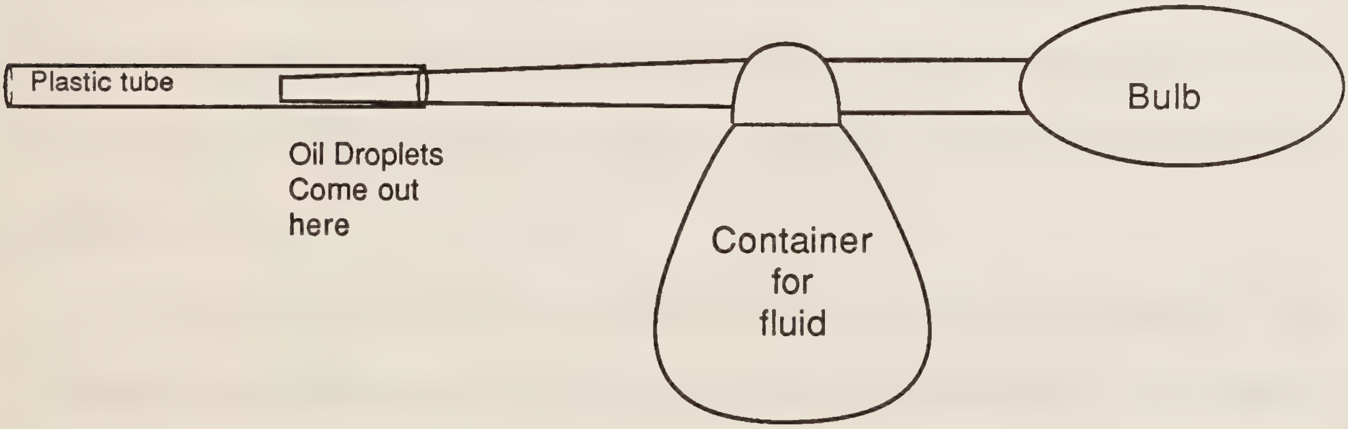


Figure 3.2, Atomizer

The first few levitation experiments used droplets with a radius in the range 1μ to 20μ, the larger ones giving better optical stability. The droplets are easy to see (even though very small) because they scatter the laser light responsible for their levitation and therefore appear to be very bright, pointlike objects.

One of the problems encountered with the atomizer was the length of the plastic tube. The tube was initially so long that only the smaller drops made it out the end of the tube. This was corrected by shortening the plastic tube.

One can certainly buy professional atomizers that put out droplets in the exact size needed, but they are expensive. Biology departments often have atomizers which produce drops (they use them for gas chromatography), but the drops are not always in the size range that is needed. Perfume atomizers can be good, if one can be found which is cheap enough. It should be noted, however, that these atomizers are designed for low viscosity fluids.

A second possible method to produce small drops, would use a hypodermic needle syringe. By putting oil in the syringe, pushing out a drop, and blasting the drop with two streams of nitrogen, a cloud of smaller drops could be formed.

A commercial aerosol may also be used to create small droplets. The problem with this method, is that the mixture of chemicals in the aerosol pollutes the droplets with volatile materials, favoring uneven heating and photophoresis.

PLASTIC BOX

The atomizer was connected by a plastic tube to a plastic box that was placed above the vertical glass cylinder. The plastic box had a hole in one side so that the plastic tube could fit in it, a hole in the bottom of the box to let the droplets fall through the tube, and a tiny hole in the other side on which a balloon was attached. The balloon was to prevent oil escaping from the plastic box and contaminating the whole room, and to provide a pressure release. Modeling clay (one could use putty) was used to assemble the setup and make joints air tight.

GLASS TUBE WITH STOPCOCK

The vertical glass tube with the stopcock permits easy observation of droplets falling down the length of the tube. A good idea of their size can be obtained from their speed of fall. Initially, a plastic tube with a valve (stopcock) in it was tried. The plastic had some charge on it, which pulled the oil droplets over to the sides of the tube. A glass tube alleviated this problem. The stopcock was useful for controlling the flow of droplets that kept coming down from the upper half of the glass tube.

A piece of tape with 0.2cm markings on it was placed on the side of the glass tube. This was useful for keeping track of where the focus of the beam was, and how fast the drops were falling.

LENS

The lens used to obtain a divergent beam was plano convex and had a focal length of 27mm. Using a lens with a smaller focal length is preferable for easy trapping of the droplets, since the beam diverges at a greater angle after it has gone through the lens, creating a larger "net" for the droplets. However, it was preferable to use a slightly longer focal length lens (27mm), since it meant easier viewing of the droplets and a larger vertical distance between droplets according to radius; i.e., in a smaller focal length lens, two droplets of different radii will be vertically closer together than in a larger focal length lens, where there will be a greater vertical distance between the two droplets.

The lens was about 7mm under the glass cover slip, giving a distance of about 2cm from the cover slip at the bottom of the glass tube, to the focus. This gave a clear distance for working when performing simple experiments. After a droplet was levitated, it could be deliberately dropped through the 2cm distance to calculate its velocity.

X-Y AXIS

The x-y axis translation system was a bit troublesome and was realized as shown in Fig. 3.3. The x-axis micromanipulator rests on the y-axis micromanipulator, and when the y-axis is moved, the mirror and everything on (and including) the x-axis moves in the y direction. This causes the two mirrors, one fixed, the other on the y-axis, to move closer together, but the laser beam remains centered on the lens and the prism. When the x-axis is moved, the

mirrors are motionless, and only the prism and the lens move, again with the laser beam remaining centered on each of them.

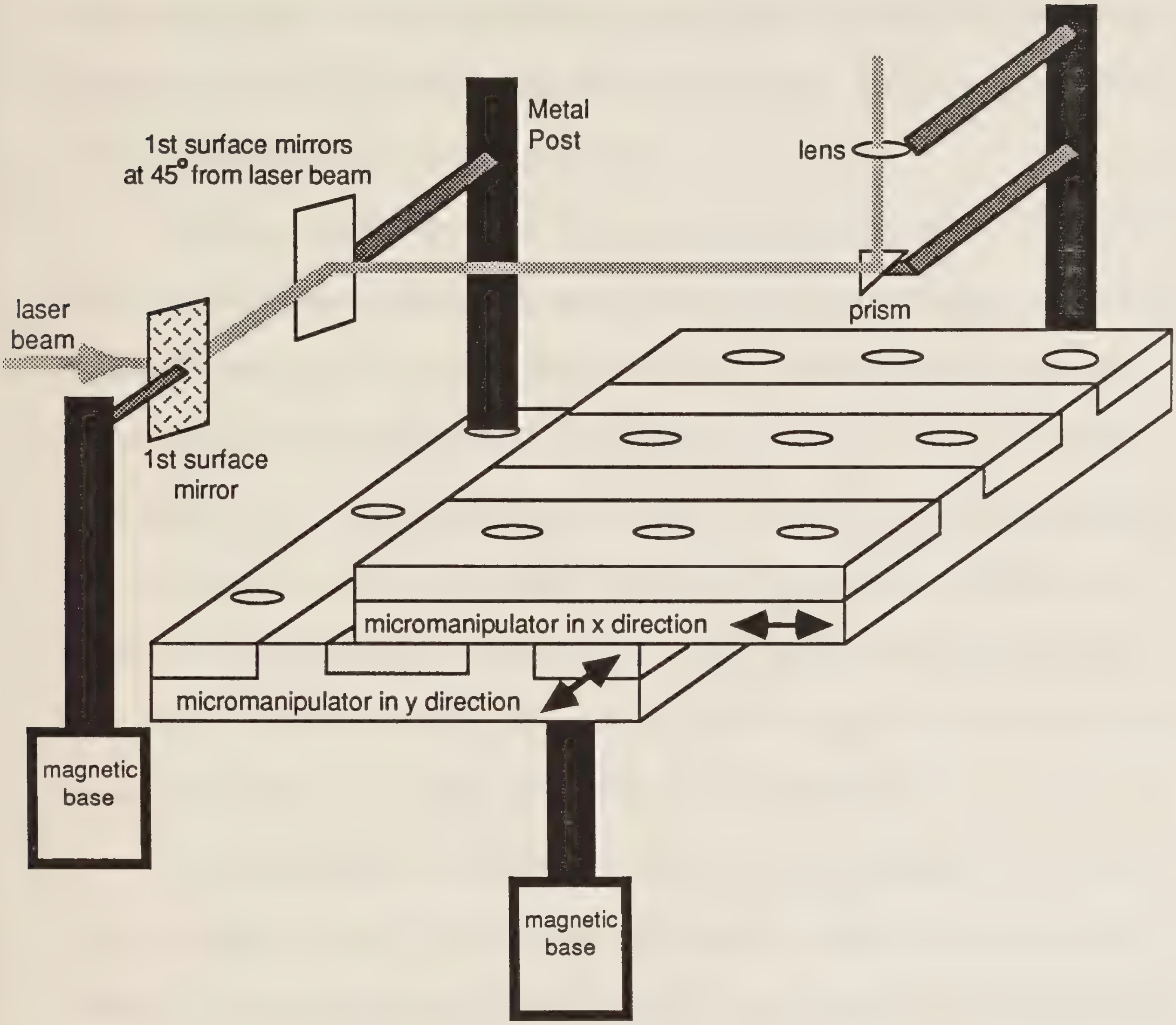

Metal Post
1st surface mirrors at 45° from laser beam
lens
laser beam
prism
1st surface mirror
micromanipulator in x direction
micromanipulator in y direction
magnetic base
magnetic base

Figure 3.3, x-y Axis Translation System

LASER

Adjustment of the laser beam to make it vertical was achieved by two methods. One was to look at the spot on the ceiling caused by the diverged

laser beam, and center this over the lens. The second was to look at the Raleigh scattering of the laser beam in air, and compare the direction of the visible laser beam to a small plumb bob hung from the side of the apparatus. Raleigh scattering is the scattering of light by particles that have dimensions small compared with the wavelength of light.

An Argon laser was used for the simple experiments in Chapter 4. Power readings were taken with a power meter with a 300mW scale, and were measured about 10cm above the prism each time. The Argon laser was part of the Model 52 Argon/Krypton Ion Laser System put out by Coherent Radiation Laboratories. The Argon laser lases at various frequencies, being strongest at 514.5nm (green) and 488.0nm (blue). The green line was used initially but then it was found that the blue line was much stronger, with a power range of 30mW to 210mW. The beam diameter of this Argon laser is 1.4mm at the $1/e^2$ intensity points of the beam. The beam divergence is 0.8 milliradians.

The experiments in chapter 5 used a Nd:YAG (Neodymium: yttrium aluminum garnet) laser. This YAG laser can put out a near IR beam at 1.06μ of about 2W, simultaneously and collinearly with a green beam of 50-100mW. The green beam is created by putting a frequency doubler in the path of the IR beam, resulting in a wave length of 532nm. The frequency doubling is also known as second harmonic generation, and is often used with neodymium lasers (which have more power than many lasers) to double the frequency of the IR output, to the visible yellow/green, where few lasers have strong outputs.

The YAG laser, when run with simultaneous green and IR beams, and

with the Q switch on, is a pulsed laser, as opposed to the Argon laser, which is a CW (continuous wave) laser. Q-switching refers to delaying the onset of oscillation in the laser cavity, then switching the cavity on at the proper moment to create a large pulse. Q-switching can be done many times a second.

TELESCOPE

A telescope intended to view small plastic spheres in the Millikan oil drop experiment was used to observe the smaller droplets and their motions. In addition, it was possible to take out the eyepiece (ocular) of the telescope, and project images of the droplets on the wall. This provided an easy way to take measurements of where the drop was with respect to the focus of the laser, and how much it moved if something was done to the drop.

VIDEOTAPES

Much of the experimentation using the Argon laser was videotaped. This served two purposes. The first purpose was to have footage of levitated droplets to show actual levitation of light pressure in action. (See Appendix A) The second purpose, was to catch "the instant" of the drop for ulterior measurements that would normally be impossible in real time.

A combination of a 2x teleconverter and a zoom lens on the color videocamera created images of the droplet that were quite large when viewed on a normal size television. The 2cm on the side of the glass tube was enlarged to about 20cm on the television screen.

CHAPTER IV

A FEW SIMPLE EXPERIMENTS

INTRODUCTION

This chapter discusses a few simple experiments performed with Dow Corning Pump oil and the blue line of an Argon laser. In this chapter and Chapter V the "size" of a sphere refers to its radius.

These experiments demonstrate that light pressure and not some other force is at work. Many of the results presented here would not be possible with forces resulting only from air currents, gravity, heat, viscosity, etc.

All but one of the experiments described herein are recorded on videotape. See Appendix A for a discussion of this videotape. Only the blue line of the Argon laser was used in the videotapes; however, the pictures presented in this chapter use the YAG laser (green/IR beam).

SIZE OF OIL DROPS

The first object was to measure the size of the oil droplets falling down the glass tube. Using the basic formula

$$r(\text{in } \mu) = \sqrt{v_T \text{ (in cm/sec)}} \times 8.8 \tag{2.13}$$

derived in Chapter 2, drops as small as 0.1μ ($v \approx 0.5$ cm/hr) were measured.

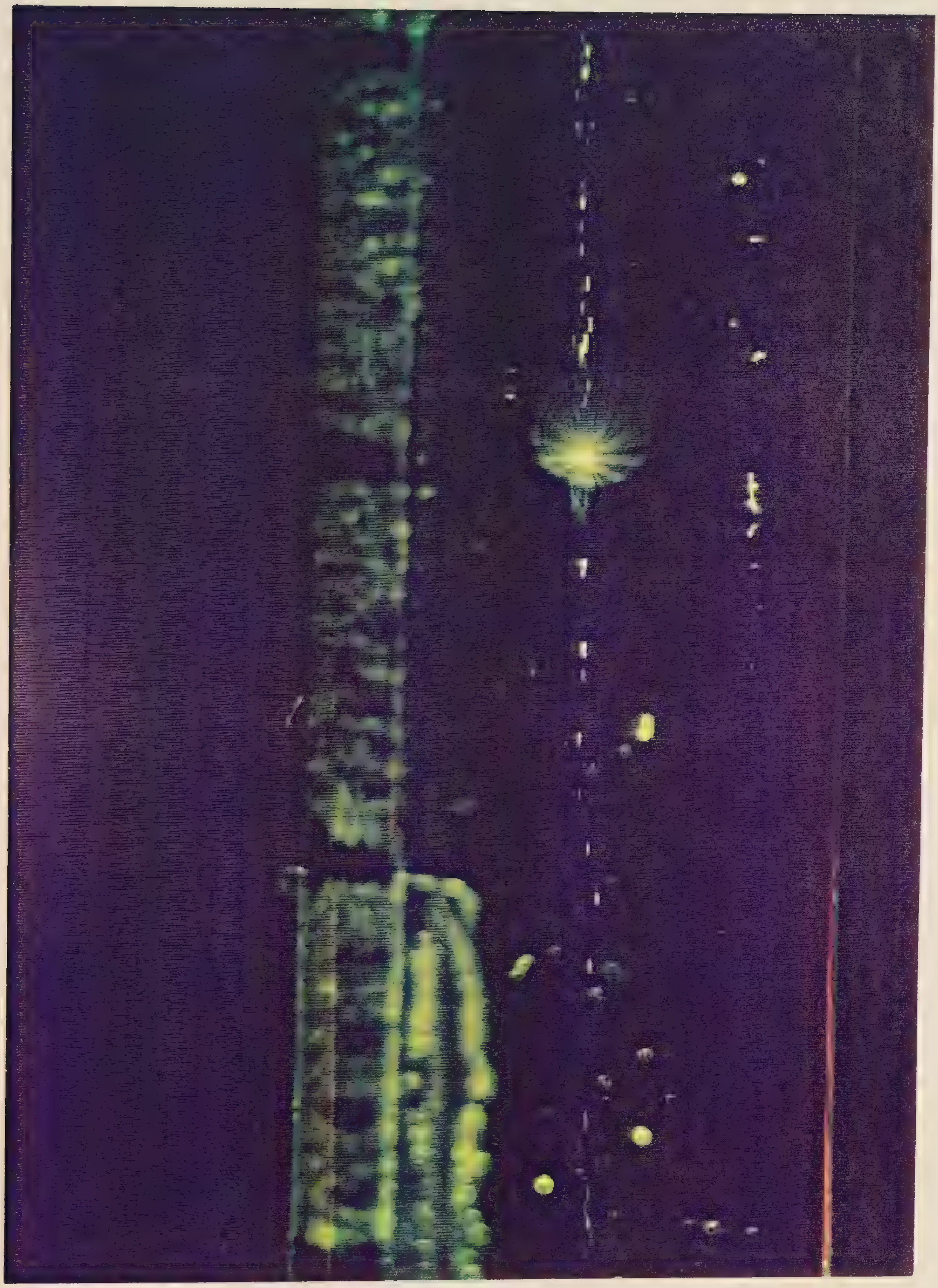
Drops could be easily generated in the 1-10μ range, and with every couple of squirts of the atomizer, drops as large as 30μ could be obtained. The atomizer produced many more drops in the <1μ range than in the >1μ range. These were not useful for optical levitation and tended to clutter up the glass tube.

The procedure for capturing an oil drop is the following. Look at the falling droplets. Select one in the 3-10μ range (or larger if possible). Watch it fall. About a cm above the focus of the laser beam, move the x-y axis of the micromanipulator and center the beam on the droplet. If the laser beam is close enough to the droplet, the droplet will draw into the center of the laser beam because of the stabilization forces mentioned in Chapter 2.

A STABLE DROP

A stable drop with a radius of approximately 10μ is shown in Picture 4.1 on page 42. Once caught, this drop could be seen across the room. The image of the trapped drop is overexposed in the center, while the images of the untrapped drops are elongated uniformly in the downward direction because of motion during the exposure. On the side of the tube is a piece of masking tape marked with a felt-tip pen in 1cm divisions, and with a pencil in 0.2cm divisions. 3cm shows in the picture. If one looks closely at the picture, one can see that the images of the untrapped drops form the geometry of the laser beam which converges, and then diverges.

A 190mW blue line Argon beam levitated a droplet for two hours. During the two hours, the drop fluctuated, dropping down, then returning to its



Picture 4.1 A Stable Drop

original position. The stabilized oil droplet was projected onto a piece of paper on the wall, allowing measurement of how much the droplet moved from its original position (see Fig. 4.1).

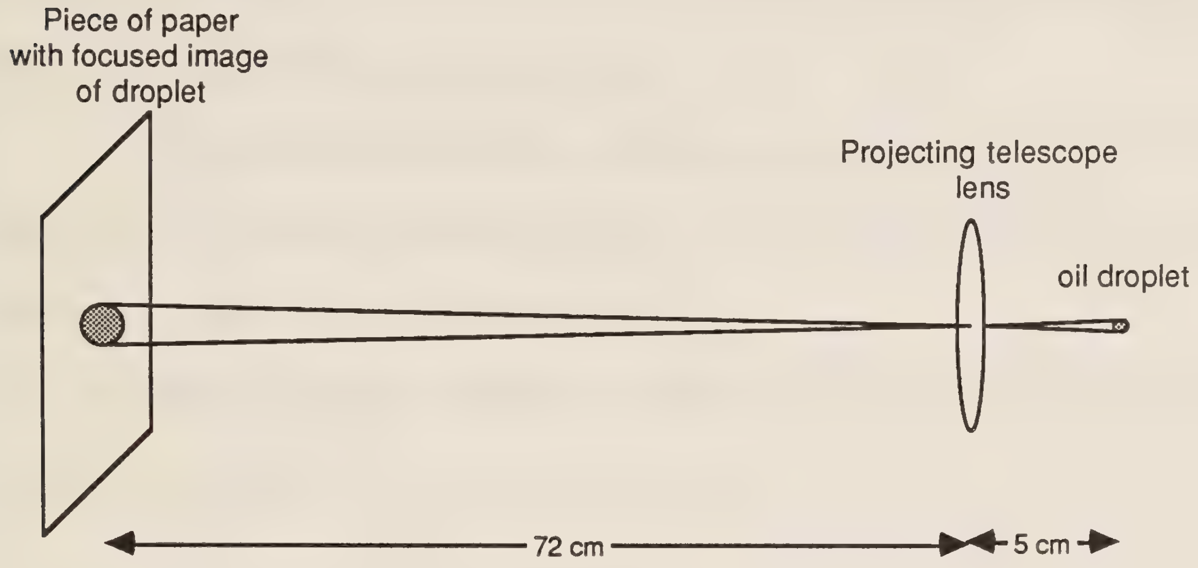


Figure 4.1 Projecting Telescope

The magnification of the projecting telescope was 14x (±10%). The fluctuations are recorded in Table 4.1.

# of minutes after capturing drop	Distance drop moved on paper from original position	Actual distance drop moved
90	4 mm	0.3 mm
110	8 mm	0.6 mm
116	10 mm	0.7 mm
118	14 mm	1.0 mm

Table 4.1 Fluctuations in 2 hr drop

At the end of the two hour period, the drop fell at the rate of about 0.3

cm/sec, suggesting a size of about 5μ. Toward the end of the period, the drop would blink out as if thrown out of the beam, only to be recaught momentarily in the beam. At two hours, the fluctuations were so great that the droplet fell. These fluctuations may have been related to the droplet photodecomposing due to the high intensity of the laser beam.

The drops which could be optically trapped ranged from about 2μ to about 10μ. In the next chapter, the higher power of the YAG laser allowed the capture of drops with radii as big as 15μ.

Different size drops stabilize at different places in the waist of the laser beam (see Fig. 4.2).

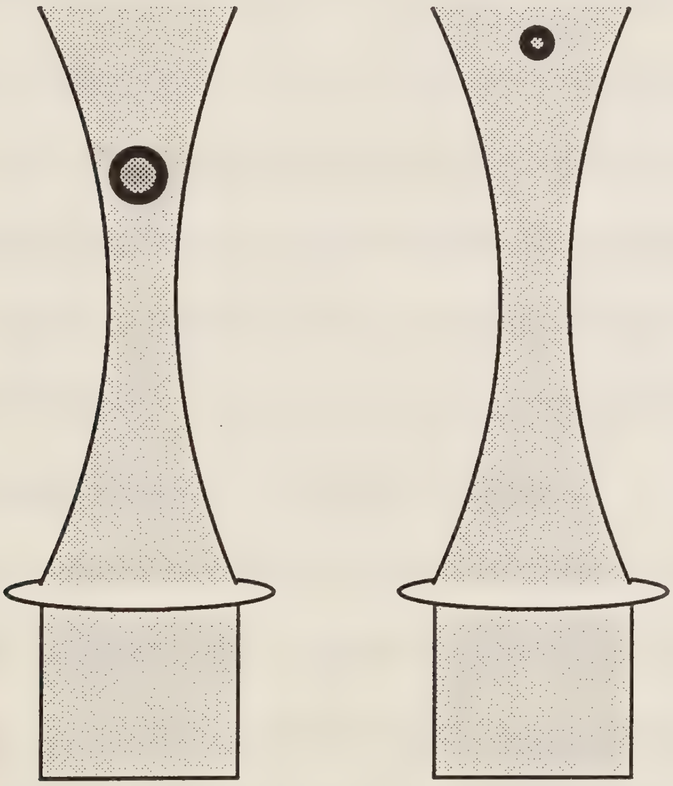


Figure 4.2, Different Size Droplets

This was demonstrated when two drops, one about 9μ, the other about 11μ, were caught together, and could be seen through the telescope right above each other.

DROPLETS TOO SMALL TO BE CAPTURED

Initially, a 1mW Helium-Neon laser was used. No drops were optically trapped, but some interesting phenomena were observed. Many of the smaller drops (<1μ), after falling down the glass tube, started to rise when they fell into the lower part of the laser beam. This was a good example of photophoresis effects, since the drops were probably rising due to the heat of the laser.

Observation of small droplets through the telescope revealed that they catch in the waist of the laser beam just below the focus, accelerate through the focus where the laser beam was more concentrated, and then continue some sort of random motion after having accelerated through the beam focus (see Fig. 4.3). This is due to the fact that the transverse forces due to light pressure are proportional not only to the area ($\sim r^2$), but to the beam intensity gradient times the diameter of the drop. As a consequence, the smaller the droplet, the larger the effect of viscous forces ($\sim r$) and of air currents.

A tiny droplet would suddenly become brighter (due to its passage through the focus of the laser beam), accelerate upwards, then slow down and become less intense. In addition, with the 1mW He-Ne laser, Brownian motion was observed. Brownian motion is the irregular motion of small particles about 1μ in diameter when they are bombarded by the molecules around them.

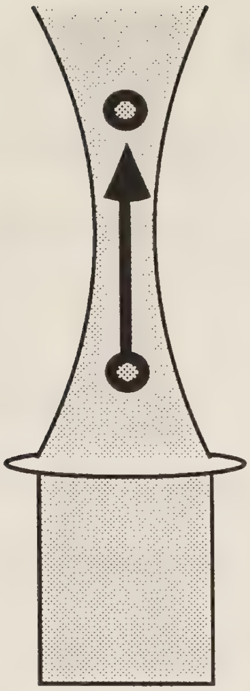


Figure 4.3, Drop Caught Below Waist

Switching from the 1mW He-Ne laser to the more powerful 200mW Argon laser allowed more thorough observation of the smaller drops. Surprisingly, there was no more Brownian motion. Instead, as before, small drops were easily captured just below the focus of the laser, where they accelerated upwards, and then slowed down and moved out of the laser beam. Somewhat larger droplets (1-2µ) could be optically trapped below the focus, accelerated to above the focus, then after they had moved out of the beam and fallen a bit, could be captured again below the focus, and the whole process repeated over again.

Although this setup has not allowed small drops (<1µ) to be optically trapped and suspended, Ashkin has presented a paper in which he used both low laser power and very small drops for levitation by light pressure.[1] This is a

difficult procedure, since the forces on the very small drops (<1 μ), like radiometric, viscous, Brownian motion, air currents, and electrostatics, tend to overwhelm the forces due to light pressure.

INTERCEPTION OF LASER BEAM

Once a droplet was levitated, the laser beam could be intercepted for a fraction of a second. It can be assumed that if the droplet is really being held in place by light pressure it would start to fall immediately. When the laser beam is returned, the droplet will be recaught by the laser beam and bounce back to its original position if it has not fallen too far. (See Fig. 4.4)

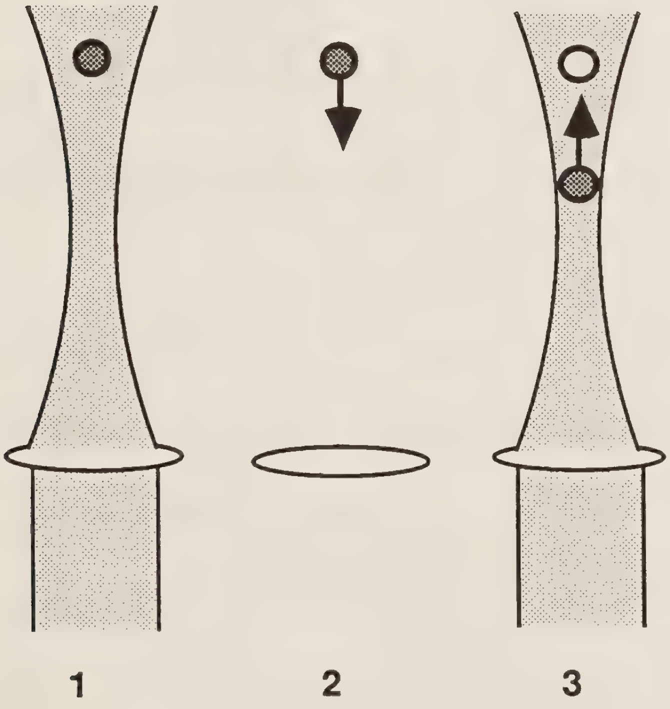


Figure 4.4 Interception of laser beam

MICROMANIPULATION

The next aspect of optically trapped oil drops is one of the most fascinating and useful. If an optically trapped drop is large enough, it will be firmly held in the optical trap by light pressure. The laser beam thus may be moved and the drop will move with it (see Fig. 4.5).

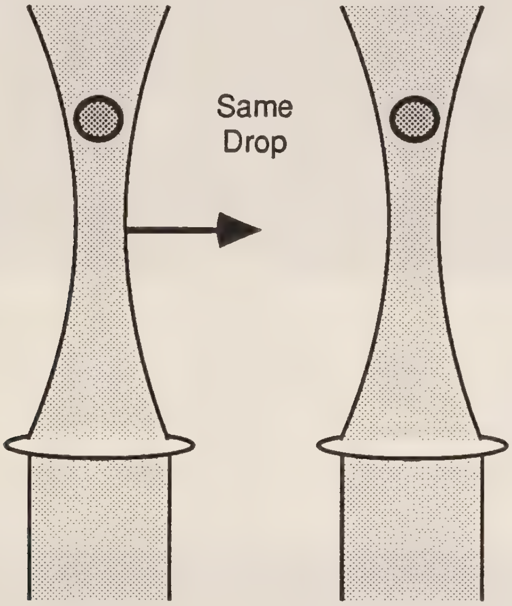


Figure 4.5 Moving Laser Beam, an OpticallyTrapped Drop

This phenomenon is shown in Pictures 4.2.1 and 4.2.2 on page 49. The 8μ droplet shown in the pictures has been moved from the left side of the glass tube (Pict. 4.2.1) to the right side of the glass tube (Pict. 4.2.2).

When moving a drop, viscous forces are destabilizing it, while radiation pressures stabilize. The larger the drop, the greater the force of radiation pressure compared to viscous forces, allowing faster movement of the droplet. For example, a 5μ droplet had no problems being moved about 0.1 cm/sec,

Picture 4.2.1

Picture 4.2.2

Micromanipulation of a droplet

while a 10µ drop could be moved about 1.5 cm/sec.

When moving the laser beam, some droplets would fall a minute distance and be recaught by the laser beam (see Fig. 4.6), resulting in a slight "bouncing" motion.

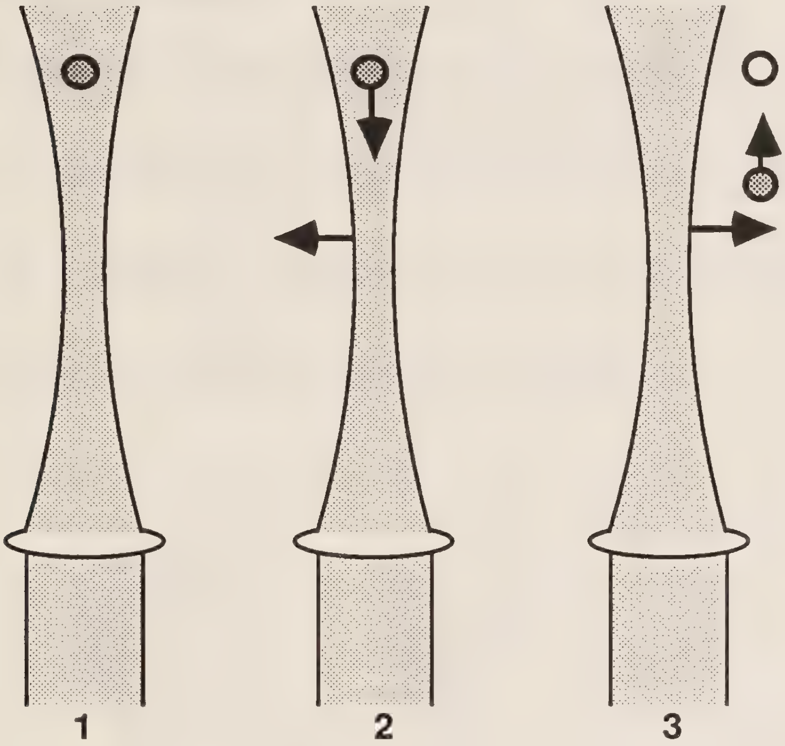


Figure 4.6 Bouncing Motion

One of the causes of the bouncing might be that the droplets are smaller and consequently are much more strongly influenced by air viscosity. When moving the droplet, the viscous forces cause the droplet to be destabilized for a fraction of a second, resulting in the droplet falling a short distance. The

"bouncing" effect occurs when the droplet is recaught by the laser beam a fraction of a second later. The bouncing motion may also be due to a dirty coverslip (from the oil droplets falling on top of it), causing the laser beam to give a slightly non-Gaussian intensity profile.

DROPPING POWER OF LASER

If with a power of P_1, a droplet is stable at a distance z_1 above the focus with an intensity I_1, and if the power is lowered to a power P_2, then the droplet will drop down to a distance z_2 above the focus of the laser beam and the intensity will be the same intensity I_1 as before. (see Fig. 4.7).

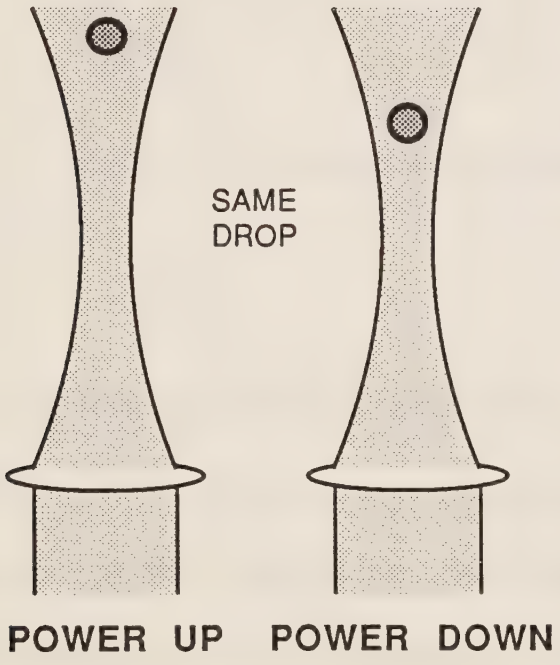


Figure 4.7 Dropping Power of the Laser

This phenomenon was verified with optically trapped drops. Power readings of the laser were determined by reading the current located on the Argon laser power supply and (after having finished with the levitated drop) measuring the power of the laser beam at each of those currents with a power meter. Movement of the oil droplet was measured by the projecting telescope (14x magnification). The same droplet was subjected to various powers of the laser to verify that it would return to the same position for its corresponding powers. Results are within about 1/2 mm for the distance the droplet moved as recorded on the paper. (See Table 4.2)

Current of power supply	Corresponding power of laser	Distance droplet moved on paper	Distance droplet moved actually
26 A	120 mW	0.0 mm	0.0 mm
20 A	60 mW	5.0 mm	0.4 mm
15 A	30 mW	6.5 mm	0.5 mm

Table 4.2 Dropping power of laser

We can verify that the intensity remains the same. Since intensity = power/unit area, or $I = P/A$, then approximate by saying that $I \sim P/d^2$ where d is the vertical distance from the focus of the laser beam to the droplet. If 1,2,3 represent the first, second, and third readings as recorded in Table 4.2, then (see Fig. 4.8) $\{d_2 = d_1 - a\}$ and $\{d_3 = d_1 - b\}$.

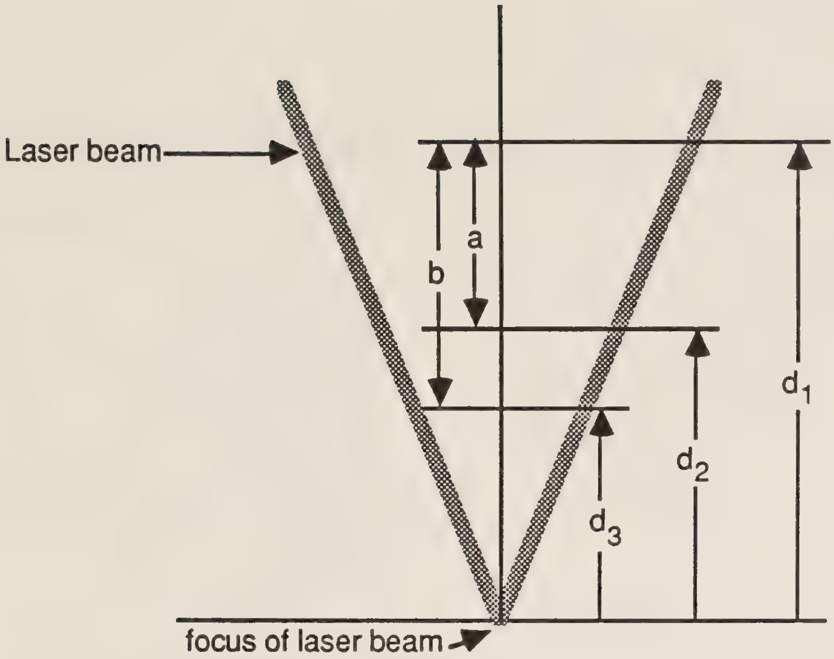


Figure 4.8 Setting relationship between a,b and d_n

In addition, since I is always constant, (4.1) implies (4.2), and with substitutions for d_2 and d_3 implies (4.3):

$$\frac{P_1}{d_1^2} = \frac{P_2}{d_2^2} = \frac{P_3}{d_3^2} = \text{const I} \tag{4.1}$$

$$\frac{d_1}{\sqrt{P_1}} = \frac{d_2}{\sqrt{P_2}} = \frac{d_3}{\sqrt{P_3}} \tag{4.2}$$

$$\frac{d_1}{\sqrt{P_1}} = \frac{d_1 - a}{\sqrt{P_2}} = \frac{d_1 - b}{\sqrt{P_3}} \tag{4.3}$$

(4.3) yields expressions for a and for b, which when divided by one another give (4.4):

$$\frac{a}{b} = \frac{\left(1 - \sqrt{\frac{P_2}{P_1}}\right)}{\left(1 - \sqrt{\frac{P_3}{P_1}}\right)} \tag{4.4}$$

From Table 4.2, $\{(P_2/P_1) = (1/2)\}$ and $\{(P_3/P_1) = (1/4)\}$. Substituting these numbers into (4.4) yields a theoretical value of $\{(a/b) \approx 0.6\}$. The actual value $\{(a/b) = (5/6.5) \approx 0.8\}$ which is 25% off from the theoretical value. This difference can be accounted for by the triangle approximation to the waist of the beam, and the 10% errors in actual measurement. It may be thus assumed that the intensities are equal at the three different points where the power was read.

INTERFERENCE FIGURES

When filming droplets a polarizing filter was used on the videocamera to reduce glare, resulting in the observation of an interesting phenomenon. With the droplet approximately at the focus point of the lens, an interference pattern was noted in the droplet. Rotating the polarizer from the original vertical position of 0 degrees, it was possible to observe the fringes of the interference

pattern sweep in and out of the sphere. (See Fig. 4.9).

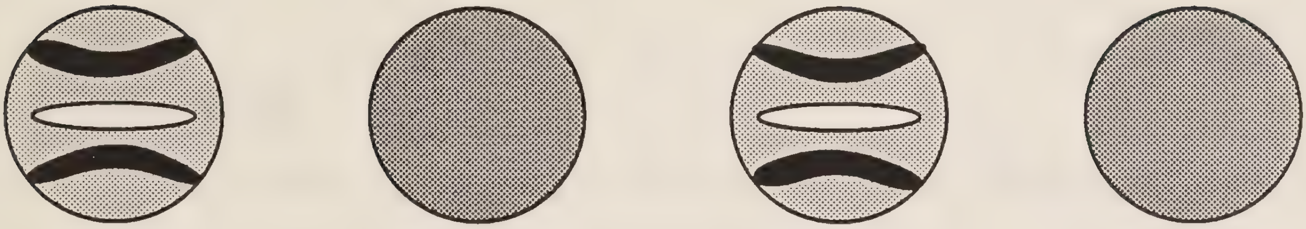


Figure 4.9 Interference Figures

In addition, at 0 and 180 degrees, there was a bright spot in the center of the sphere, and at 90 and 270 degrees the droplet appeared to be at extinction. Mie scattering and the fact that the Argon laser beam is partially polarized could give a partial explanation for the observed optical patterns.

CONCLUSION

The majority of the simple experiments done in this chapter show that light pressure is indeed at work, and that other forces can be overcome. This suggests that light pressure can now be used as a tool for investigating other phenomena in physics. An example of such investigation will be discussed in the experiment in chapter 5.

CHAPTER V

LEVITATING DYE-DOPED DROPLETS

INTRODUCTION

This chapter will discuss the results of work done with levitated drops of polyethylene glycol containing Rhodamine 6G in solution.

In 1980, Benner et al. reported results of fluorescence from a dye-doped polystyrene sphere suspended in water which had been illuminated by an Argon laser.[1] Then, in 1984, Tzeng et al. observed laser emission from individual ethanol droplets containing Rhodamine 6G by letting the drops fall and illuminating the droplets with a side laser beam.[2] In 1985, the same group published a paper where they had observed shape oscillations of individual flowing droplets due to internal pressure variations caused by lasing.[3] Then, in January of 1986, Qian et al. presented some pictures and a discussion of dye-doped lasing droplets.[4] These four papers were done at the Center for Laser Diagnostics, Yale University.

In these papers, the lasing or fluorescing was always pumped with a laser, but the drops were not levitated at the same time. Instead, in each case, the spheres fell, and laser light was focused on the falling spheres from the side. Nowhere in the literature, to this author's knowledge, has it been recorded that a stably levitated, dye-doped drop has simultaneously been caused to fluoresce or to lase. This is the object of the experiment presented in

this chapter.

THEORY

The basic operation of a dye laser requires the absorption of radiation at a given wavelength and a strong fluorescence at a longer one. Rhodamine 6G is a dye commonly used for the purpose. In polyethylene glycol, its fluorescence peak is in the neighborhood of 600nm (yellow). Lasing can be obtained if the fluorescence light is reflected inside the droplet in a polygonal pattern whose perimeter is an integral number (n) of wavelengths (λ_n), i.e. $2\pi r = n\lambda_n$. As an example, a 10μ drop, has a perimeter of $2\pi r \approx 63\mu$. The wavelength inside a droplet with n=1.5 using a green beam (532nm) is about λ=350nm. If we have two different modes, one at n and λ_1, the other at (n + 1) and λ_2, then

$$2\pi r = n\lambda_1 = (n+1)\lambda_2 \tag{5.1}$$

which gives a separation between modes of

$$\Delta\lambda = \frac{\lambda}{n} = \frac{\lambda}{\frac{2\pi r}{\lambda}} = \frac{\lambda^2}{2\pi r} = \frac{(350\text{nm})^2}{2\pi(10\mu)} \approx 2\text{nm} \tag{5.2}$$

The small perimeter of the droplet gives a large separation between modes of approximately 2nm.

ARGON LASER

A concentration of 10^{-4} Rhodamine 6G in 400MW Polyethylene Glycol (Carbowax 400) was used first. (Ethylene glycol is antifreeze.) When a sphere of this liquid was optically trapped with a 200mW blue Argon beam, and observed through goggles that remove the blue laser light, a deep red was viewed in the forward scattering direction. The goggles reduced the intensity of the light by quite a bit. A spectrophotometer could have been used to ascertain the spectral properties of the emitted light. The deep red would be characteristic of the lasing output of a dye-doped polyethylene glycol drop. The drops that Qian et al. observed were lasing in the red.

The solution of dye-doped polyethylene glycol was then increased to a concentration of 2.5×10^{-2}. As the spheres fell down the glass tube, hints of yellow could be seen. Then, when the spheres entered the laser beam, they accelerated in the downward direction. This was clearly verified with videotapes. Photophoresis effects are assumed to be responsible. The presence of the dye increases the absorption of the light, and therefore heating effects occur.

When a large (about 12μ) sphere of this solution was finally optically trapped, it exploded a fraction of a second later into thousands of tiny droplets that then drifted up the laser beam. This was repeated a number of times and was confirmed with the use of the videotape. When watching the videotape, however, there seemed to be a brief instance when the droplet glowed very bright, before it exploded. The color of the glow could not be ascertained from

the videotapes because of poor color balance, and while doing the experiment the action happened too quickly to notice the colors involved.

YAG LASER

The YAG laser was a partial solution to the problems of overheating. The IR beam at 1064nm of about 1.5W does not affect the dye because the dye does not absorb at that wavelength. The green beam that is collinear with the IR beam can be controlled so that it is 20mW or 200mW. In addition to the low IR absorption of the dye, the YAG laser is pulsed, giving the dye a chance to cool off from any residual heating effects.

The dye concentration used was 3×10^{-4}. As the drops fell, beautiful yellows to deep golden yellows could be seen. The drops were fluorescing strongly as they fell down the glass tube. Some drops that were optically trapped, appeared to be yellow for the first few seconds, but would then turn to green.

Finally, a 10µ drop was caught that had a hint of yellow in it (not the deep golden yellow viewed in a few droplets) and it stayed around for a minute or so. A slide was taken and the result is presented here. In Picture 5.1, on page 61, the drop appears white due to emulsion saturation problems. It is shown to give an idea of where the drop is with respect to the setup. A segment of Picture 5.1 has been enlarged, with special care to retain the original color balance, and is shown in Picture 5.2 on page 62. To give an idea of the scale in both pictures, cm markings have been put next to them. If one uses a

magnifying glass on the image of the drop in Picture 5.2, one will see a yellow ring, with a white center, and a hint of green on the outside. This is probably due to the color saturation limitations of the film, and the high intensity scattered by the drop. The drop shown is fluorescing in the yellow.

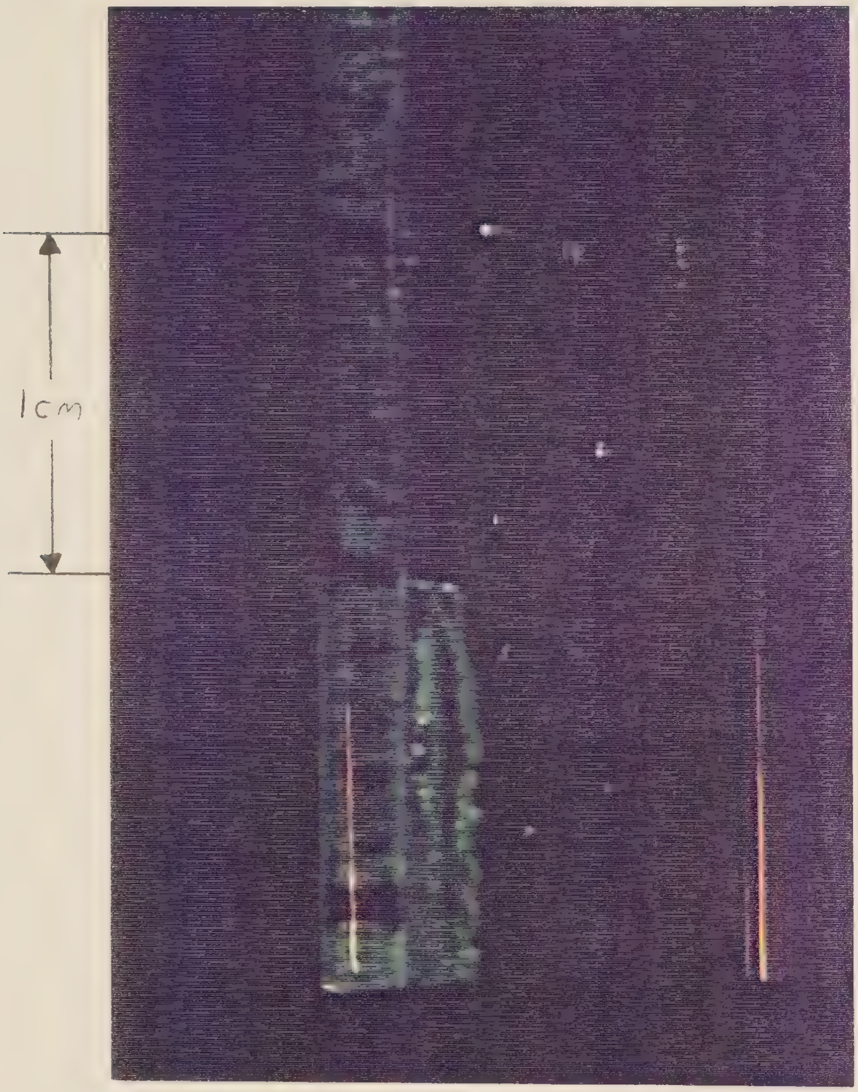
FURTHER WORK

After obtaining fluorescence and the possible lasing dye-doped drops, an attempt was made to obtain larger drops by using an inkjet from Hewlett Packard, analogous to those used in inkjet printers.[5] Problems were encountered because of the viscosity of the solution.

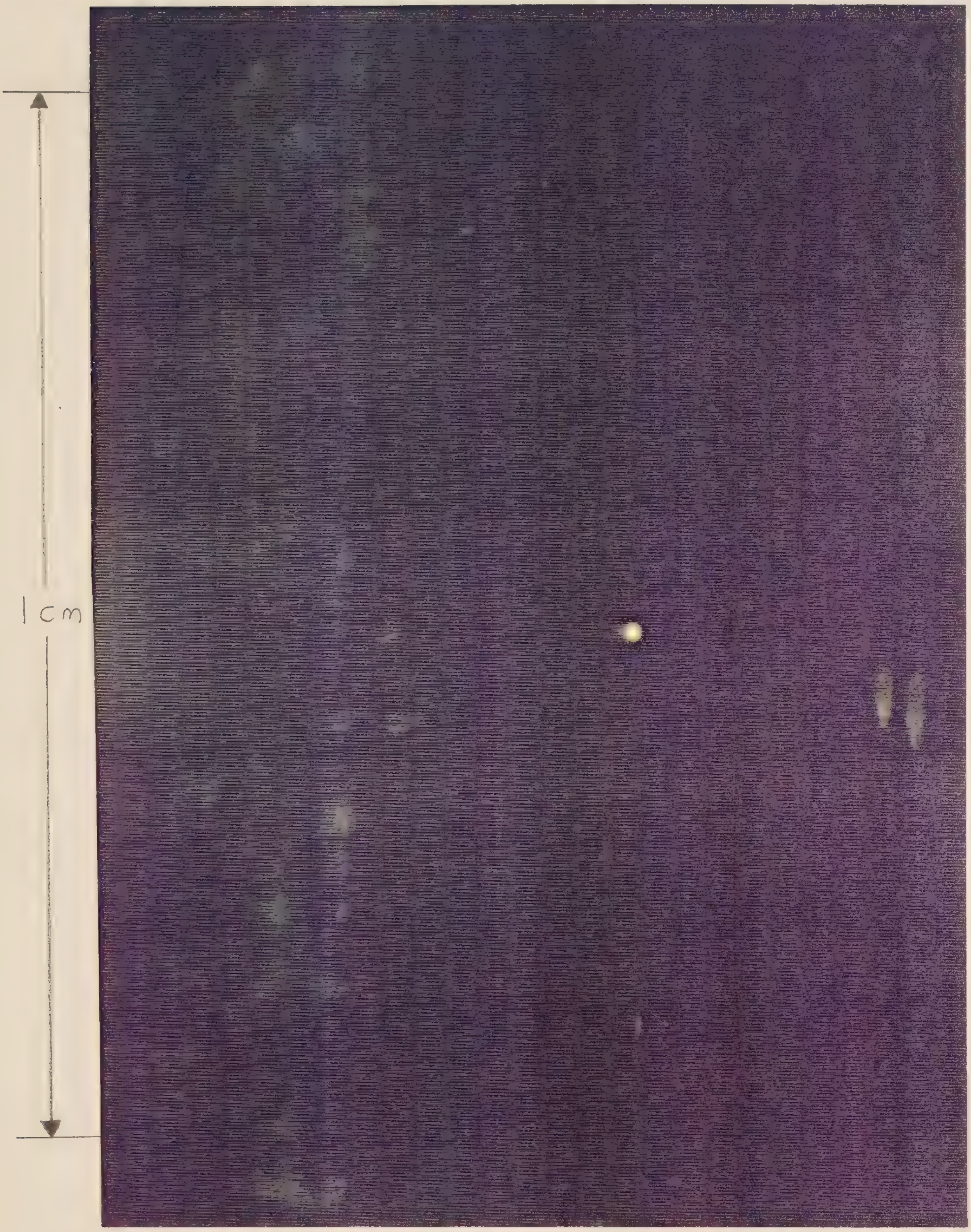
The inkjet would have been useful, because it can give larger, more uniform drops in a very repeatable way. This would have made capture of the drops easier. If a large enough drop is stabilized, microscopic observation becomes possible, and the lasing modes can be directly observed with the help of appropriate filters.

CONCLUSION

An optically levitated drop of a dye-doped liquid was seen to fluoresce. There is a possibility that lasing was also seen, with the Argon laser. These two observations indicate that it is possible to create a levitated ring dye laser that uses the light intensity of the laser beam to keep it optically levitated, and at the same time provides the pumping power needed for lasing.



Picture 5.1 Fluorescing droplet, burned out



Picture 5.2 Fluorescing droplet, enlarged view

NOTES

CHAPTER I

[1] Unless indicated, all of the references to names in this chapter are from Arthur Ashkin, "The pressure of laser light," Scientific American, 226(2), February, 1972, pp. 63 -71. The dates for all of the names were obtained from Webster's New Collegiate Dictionary, 1981.

[2] This reference to Peter Apian was obtained in a seminar given by Alan F. Bentley, Tuesday, April 8, 1986 at Reed College. It was obtained from Bulletin de la Société Astronomique de France, 1910.

[3] Prof. J. H. Poynting, "Radiation pressure," Proceedings of the Physical Society of London, XIX, 1903-1905, pp. 487-490.

[4] Lloyd Motz and Anneta Duveen, Essentials of Astronomy (Belmont, CA: Wadsworth Publishing Co., 1966), pp. 232-234.

[5] Taken from the instructions that came with one of my solar radiometers (made in West Germany). "Depending on the power of the light a rotation of 3000 revolutions per minute can be reached by the radiometer which is a technically interesting and amusing article for the modern home."

[6] Note that in the Scientific American article of February 1972, they list Nichols, as being Ernest F. Nichols. In Optics by Hecht & Zajac, on p. 48, his name is listed as Edward Leamington Nichols. I am not sure which one is correct.

[7] J.R. Zacharias, M.I.T., "The pressure of light," PSSC Film No. 0202, 23 minutes, 1958.

[8] Arthur Ashkin, "Acceleration and trapping of particles by radiation pressure," Physical Review Letters, 24(4), January 26, 1970, pp. 156-159.

[9] Ashkin and J. M. Dziedzic, "Optical levitation by radiation pressure," Applied Physics Letters, 19(8), October 15, 1971, pp. 283-285.

[10] Ashkin, "The pressure of laser light," Scientific American, 226(2), February 1972, pp. 63-71.

[11] Ashkin and Dziedzic, "Stability of optical levitation by radiation pressure," Applied Physics Letters, 24(12), June 15, 1974, pp. 586-588.

[12] Ashkin and Dziedzic, "Optical levitation of liquid drops by radiation pressure," Science, 187, March 21, 1975, pp. 1073-1075.

[13] Ashkin and Dziedzic, "Optical levitation in high vacuum," Applied Physics Letters, 28(6), March 15, 1976, pp. 333-335.

[14] Ashkin and Dziedzic, "Feedback stabilization of optically levitated particles," Applied Physics Letters, 30(4), February 15, 1977.

[15] When I was at Lawrence Livermore Laboratories during the summer of 1985, an experiment was mentioned where certain biological cells were separated from other cells using light pressure.

[16] Ashkin and Dziedzic, "Observation of light scattering from nonspherical particles using optical levitation," Applied Optics, 19(5), March 1,

1980, pp. 660-668.

[17] Ashkin and J.P. Gordon, "Stability of radiation-pressure particle traps: An optical Earnshaw theorem," Optics letters, 8(10), October 1983, pp. 511-513.

[18] Ashkin and Dziedzic, "Interaction of laser light with magnetic domains," Applied Physics Letters, 21(6), September 15, 1972, pp. 253-255.

[19] Ashkin and Dziedzic, "Observation of a new nonlinear photoelectric effect using optical levitation," Physical Review Letters, 36(5), February 2, 1976, pp. 267-270.

[20] Ashkin, "Atomic-beam deflection by resonance-radiation pressure," Physical Review Letters, 25(19), November 9, 1970, pp. 1321-1324.

[21] Ashkin, "Trapping of atoms by resonance radiation pressure," Physical Review Letters, 40(12), March 20, 1978, pp. 729-732.

[22] Bjorkholm, Freeman, Ashkin, and Pearson, "Observation of focusing of neutral atoms by the dipole forces of resonance-radiation pressure," Physical Review Letters, 41(20), November 13, 1978, pp. 1361-1364.

[23] Ashkin, "Stable radiation-pressure particle traps using alternating light beams," Optics Letters, 9(10), October 1984, pp. 454-456.

CHAPTER II

[1] Arthur Ashkin, "The pressure of laser light," Scientific American, 226(2), February, 1972, p. 64.

[2] Two places where one can buy calibrated glass and polystyrene microspheres, both in suspension and dry, are Duke Scientific Corporation, Palo Alto, CA; and National Bureau of Standards, Washington, D.C (listed under Standard Reference Material 1003a, 1004, 1017a, 1018a, 1019a, and 1960).

[3] Jin Seung Kim and Sang Soo Lee, "Radiation pressure on a dielectric sphere in a gaussian laser beam," Optica Acta, 29(6), 1982, pp. 801-806.

CHAPTER III

[1] Antonino B. Pluchino, "Radiometric levitation of spherical carbon aerosol particles using a Nd:YAG laser," Applied Optics, 22(12), June 15, 1983, pp. 1861-1866.

[2] M. Lewittes, S. Arnold, and G. Oster, "Radiometric levitation of micron size spheres," Applied Physics Letters, 40(6), March 15, 1982, pp. 455-457.

[3] "Information about silicone diffusion pump fluids" from Dow Corning Corporation, Midland, MI 48640.

[4] Ashkin and Dziedzic, "Optical levitation of liquid drops by radiation pressure," Science, 187, March 21, 1975, p. 1074.

CHAPTER IV

[1] Ashkin and Dziedzic, "Optical levitation of liquid drops by radiation pressure," Science, 187, March 21, 1975, pp. 1073-1075.

CHAPTER V

[1] R.E. Benner, P.W. Barber, J.F. Owen, and R.K. Chang, "Observation of structure resonances in the fluorescence spectra from microspheres," Physical Review Letters, 44(7), February 18, 1980, pp. 475-478.

[2] H.M. Tzeng, K.F. Wall, M.B. Long, and R.K. Chang, "Laser emission from individual droplets at wavelengths corresponding to morphology -dependent resonances," Optics Letters, 9(11), November 1984, pp.499-501.

[3] H.-M. Tzeng, M.B. Long, R.K.Chang, and P.W. Barber, "Laser-induced shape distortions of flowing droplets deduced from morphology-dependent resonances in fluorescence specta," Optics Letters, 10(5), May 1985, pp.209-211.

[4] Shi-Xiong Qian, Judith B. Snow, Huey-Ming Tzeng, Richard K. Chang, "Lasing droplets: Highlighting the liquid-air interface by laser emission," Science, 231, January 1986, pp. 486-488.

[5] "Thinkjet printers," Hewlett Packard Journal, 36(5), May 1985, pp. 1-40.

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APPENDIX A

VIDEOTAPE

A fifteen minute videotape on VHS film was created from two hours of videotaping done using a Panasonic Videocamera with Beta film. A copy of this videotape will be left with the following people: the secretary of physics at Reed College, Jean Delord, Richard DeFreez of Oregon Graduate Center, and myself.

The laser used for all of the experiments recorded in the videotape was an Argon laser, 488nm (blue), at about 200mW unless indicated otherwise. On the side of the glass tube there is masking tape which is marked with magic marker in 1cm segments, and pencil in 0.2cm segments. Normally, when viewing the videotapes, only the 1cm markings are visible. In many segments, two bright images will be seen: the levitated droplet, and a reflection of the drop on the side of the glass tube.

The next two pages are a summary of the action that appears on the videotape.

Abbreviations:

DFB: **D**roplet **f**alling **b**efore being optically levitated

CD: **C**apturing a **d**roplet

SD: An optically trapped **s**table **d**roplet

ILB: **I**nterception of the **l**aser **b**eam

M: **M**icromanipulation of laser beam

BM: **B**ouncing **m**otion

DP: **D**ropping **p**ower of the laser

A: A small droplet **a**ccelerated through the focus of the beam

DFA: **D**roplet **f**alling **a**fter being optically levitated

DS = : **D**roplet **s**ize radius equals about

# on VHS Videotape	Description of what is happening	
0000-0037	Argon laser, power supply for laser, and experimental setup	
0040-0058	DFB, CD, SD,	DS=7μ
0060-0097	DFB, CD, SD, BM, DFA,	DS=4μ
0100-0116	SD, ILB, M, DFA,	DS=5μ
0119-0139	DFB, CD, SD, ILB, DFA,	DS=5μ
0141-0164	SD, ILB, M, DFA,	DS=4μ
0168-0179	SD, DP,	DS=2.5μ
	Power going from 160mW to 40mW to 160 mW.	
0182-0194	SD, DP,	
	Power going from 220mW to 65mW to 220mw.	
0197-0217	A,	
	Levitation chamber is full of small drops (<1μ), the lens and the laser beam can be seen moving	
0219-0267	SD, M & BM, DFA,	DS=2.8μ

0269-0295	SD, M, DFA, DS=5µ In this segment, the optically levitated drop can be clearly seen moving from one side of the glass tube to the other in one direction, while the reflection of the drop moves in the opposite direction. Towards the end of this segment, Caustics can be seen in the reflection. These Caustics are folding in and out.
0297-0346	Interference fringes. The polarizer starts at 0 then goes to 45, 90, 180, 270, and 360 degrees.
0349-0378	Dye-doped drop ($2.5x10^{-2}$ concentration) accelerating down due to photophoresis effects.
0381-0385	Same as above
0388-0521	A dye-doped drop ($2.5x10^{-2}$ concentration) exploding, then drifting up laser beam.
0524-0558	A dye-doped drop ($2.5x10^{-2}$ concentration) that has already exploded, watching the drops accelerate from below focus to above focus, and drift up beam.

REED COLLEGE

Seventy-ninth Commencement

Sunday, May twenty-fifth

Nineteen Hundred Eighty-six

Two o'Clock

Marshals

Commencement Marshal: Peter J. Russell, Professor of Biology
Student Marshals: Robert E. Reynolds, Professor of Physics;
Ellen Keck Stauder, Assistant Professor of English
Faculty Marshals: Gail Berkeley, Assistant Professor of English Literature/Humanities;
David Groff, Dean of Students, Assistant Professor of History/Humanities

A Note on Academic Regalia

Academic regalia worn at commencement and on other ceremonial occasions at colleges and universities serves not merely to lend dignity and color to such occasions but to reveal different types of academic achievement through the use of different styles of gowns and hoods and varying colors.

Based on the costumes worn at universities in the 14th and 15th centuries, especially at Oxford and Cambridge in England, today's academic dress is essentially the same as that standardized in the United States by the Intercollegiate code adopted in 1895. It includes the familiar square mortarboard cap with a tassel which may be black, gold, or an appropriate color (e.g., pink for a degree in music), in addition to three styles of gowns and hoods representing bachelor's, master's and doctor's degrees.

The color and design of gowns are not rigidly prescribed. Besides black, which is most usual, red and blue gowns are common. The bachelor's gown has a long pointed sleeve, the master's a long closed sleeve with a slit for the arm at the elbow, and the doctor's a very full, bell-shaped sleeve with three velvet bands matching the velvet facing of the gown opening. The velvet on the doctor's gown often is in a color appropriate to the wearer's field of study.

Of the three styles of hoods, the doctor's is naturally the most elaborate. The bachelor's hood is rarely used, and on occasion any of the gowns may be worn without a hood. All three hoods are made of material to match the gowns and are lined in the official color of the institution which conferred the degree, with a chevron used for a second color if needed. The colored velvet binding indicates the academic area in which the degree was earned; for example, white for liberal arts, pink for music, yellow for science, purple for law, red for theology, green for medicine, blue for philosophy.

A Humanities Award, established in memory of Reed Professor William T. Lankford III, was awarded this year to Reed senior John M. Trombold.

The Program

Prelude and Processional*
Dances from the Sixteenth Century
Portland Brass Quintet
Robert Rutherford, *trumpet* Larry Johnson, *French horn*
Sally Nelson, *trumpet* Randall Malmstrom, *trombone*
James Sandberg, *tuba*

Introductory Remarks
Paul E. Bragdon
President of the College

Address
''Farewell Liberalism Forever''
Dr. Gregory B. Wolfe, '43
President, Florida International University

Conferring of Degree of Bachelor of Arts
President Bragdon

Recessional*
Trumpet Voluntary, Clark, 1692
Portland Brass Quintet

Graduates and guests are invited to the Commencement reception on the lawn.
(In the Commons, in case of rain.)

*The audience is requested to rise for the processional and recessional.

Graduating seniors are listed alphabetically under each of Reed's five academic divisions, followed by Interdisciplinary Majors and master's graduates. The listing includes the academic department in which the student majored, followed by the title of the student's senior thesis.

The Arts

James Appleton (as of 12-6-85)
Art
Works on Paper and Canvas

Gretchen Alyssa Gibbs
Art
Painting Shadows: Making Sense

Emily Stewart Harris
Theatre
Imagination and Coherent Context:
Sam Shepherd's The Unseen Hand

Holly M. O'Neil
Theatre
Theatre and Ritual Transformation:
Tales of Spider Woman and the Spinnerets

Christopher Dana Scovel
Art
Typological Theory and Design Methodology in Architecture

Sarah Khatoon Soffer (as of 12-6-85)
Art
Recent Sculptures

Grant G. Stipek
Art
Frank Lloyd Wright's Concept of Organic and his Ideal in Man

George J. Wehn
Art
Paintings

History and Social Sciences

William C. Abendroth
Economics
Unjust Dismissal: A Proposed Statutory Remedy for Oregon

E. Mikal Anderson
Economics
The Bull Run Watershed: Water of Life and the Logger's Lament

Todd H. Basch
History
Beat Roads and Reason Avenue: Jack Kerouac, the New York Intellectuals, and the Split of Spirit and Politics

Matthew P. Bergmán
Sociology
Secularization, Legitimation and Anomie: The Case of School Prayer

Jamie A. A. Bollenbach
History
Democracy and the Wild, Wild West

Donna Lynn Brune
Economics
The Economic Efficiency of Corporate Mergers and Acquisitions

John E. Burrell
History
Tanks for the Memories, or Allied Armor Strategy and Deployment in Europe 1944

Callie Jean Chandler
Political Science
Congress and the Defense Budget: A Constructive Critique of the Armed Services Committees

George Riely Dobbin
Anthropology
Digging for Goldie: Alexander Goldenweiser's Contributions and His Iroquois Notes

Braden Dong
Political Science
A Comparative Analysis of Two Conceptual Critiques of Technology: Ellul and Mailer

Sarah Hautzinger (as of 1-23-86)
Anthropology
What I Did on My Summer Vacation: Carnes: A Deviant Subculture

Barnard Helman
History
Resettling the Evacuees: The Return of the Japanese-Americans to Oregon

Benjamin M. Joseph
History
The Historiography of a Strange War: Chile's Civil War of 1891

Lisa Renee Joyce
History
Creators of Culture: Abigail Scott Duniway and Eva Emery Dye of the Oregon Woman Suffrage Movement

Scott Jonathan Kaplan
Political Science
The Limits to Religious Action: Principled Ways of Drawing the Line

Ruth Kennedy (as of 12-16-85)
Anthropology
In Pursuit of Paradise: A Case Study of Jehovah's Witnesses, A Modern Millenarian Movement

Aslam Qadar Khan
Economics
Ideology or Economics? *A Look at the Public Owned Corporations in the Context of Industrial Growth and Development in India Since 1965*

Kim R. Kunkle
Political Science
The Politicization of the Private: Gender Politics and the Women of Japan

Kent Allen Lind
Political Science
PACS AMERICANA: The Impact of Dollars on Democracy in the United States

Allyson Lynch (as of 4-29-86)
History
The Salem Witchcraft Prosecution, 1692: Wonders of the Visible World

John Francis Manzo
History
Ideas in Context: The Sociology of Robert Ezra Park

Kathryn Crystal Mapps
History
In His Image: The Rise of Slave Religion and African Churches

Fiona Martin
Anthropology
Between Dissemination and the Semiological Illusion: Problems in the Textual Interpretation of Initiation Rituals and the Liminal Period

Neville McClure
Political Science
Maximizing Benefits Under Hegemony: Canada-U.S. Relations Since 1945

Bryan McGowan (as of 12-9-85)
History
Creating an Intellectual Aristocracy: Liberalism and the Political Thought of Walter Lippmann

Demetra Zoe Mendell
Political Science
Self to Metaself: A Public Project

Anne W. Muller (as of 5-20-86)
History
No Villains, No Heroes: The Oregon School Bill Controversy, 1922

Alexander C. Patterson
Anthropology
Appearance Only: Traditionalization in Hindi Cinema

Adam Landis Penenberg
Economics
Causes of Effects of Rural-Urban Migration in the Third World

James Dolan Reid
Anthropology
Kill the Head and the Body Will Die: An Exploration of Classic Mayan Chronology

Deborah Rogers (as of 2-14-86)
History
The History of Weather: 1846-1945

Paul Roskin
Economics
Balancing External Adjustment Costs and Economic Growth: The Case of Plant Closing Legislation

Christopher Simpson (as of 9-17-85)
History
Images of Totalitarianism: Theodor Adorno's Typological Hermeneutic

Cary W. White
Political Science
Subsidized Inner-City Middle Income Housing: Is It Life or Death for the Nation's Aging Cities

Benjamin Zolton Wirtschafter
History
The IWW and the Overalls Brigade: The Impact of Northwestern Wobblies on the One Big Union

Thomas Lewis Wright
History
The Transformation of Social Intervention in the American Family, 1880-1910

Jeffrey D. Young
History
A Historical Reading of Emile Durkheim

Literature and Languages

Heather A. Bell
English
Kathy Acker's Blood and Guts in High School: *"So We Create This World In Our Own Image"*

Katie Christensen
English
In A Small City and Other Stories

Allison Cummings
English
Ruptures in logic: where's the crack in the joke?

Jeffrey Scott Darnall
English
The Swan Ranch

Dayne Freitag
English
"Bond and Free": Tracking Robert Frost Within the Confines of His First Four Books: A Discussion of the Poet as Editor

Andrew R. Gaudreau
English
Reader Responsibility and the Articulation of Desire in the Poetry of W. B. Yeats

Simon Andrew Glickman
English
A Limited Number of Surprises

Mark Haag (as of 1-23-86)
Russian
Derzavin's Poetic Pretensions, or, Odes Not About God

Christopher Hall
English
Sam Shepard: American Playwright

Rebecca Lynn Herlinger
English
Structuring Disorder: Narrative and Thematic Development in the Novels of Margaret Drabble

Douglas E. Hill (as of 5-14-86)
French
Antonin Artaud and Cruelty of Representation

Darcy Jill Jorgensen
Russian
Heresy and Revolution: Four Short Stories by Evgenijzamjatin, A Translation and Analysis

Phyllis Maria Manos
English
The Arrangement of Words: Ezra Pound, William Carlos Williams, and the Visual Arts Comparison

Alison McAlpine
English
Before All This: *A One-Act Play*

Susan Beth Poltun
French
The Uses of Simplicity: The Poems of Robert Desnos

Kathryn Mary Pratt
English
Chastity and Feminine Experience in Book III of Spenser's The Faerie Queene

Laurie Frances Reid
French
Resistance Through Rhetoric: Francis Ponge's Verbal Violence

Mark Lowell Share
English
Fixed Thoughts and Roving Eyes: Versions of Learning in The Faerie Queene

Sharon L. Snyder
English
Thoughts of the Staircase

Valerie Chandra Thomas
Classics
Sappho's Lyrics: A Study in Desire

Sarah Ann Wadsworth
English
To the Lighthouse *as Elegy: A Study in Genre*

Ruthanne Williams (as of 12-20-85)
General Literature
Fictional Fates: Heroism and Hero Worship in Geroj Nashego Vremyeni and Le Rouge Et Le Noir

Bronwen Aliina Wirta
English
The Heretic Narrative: The Modern Gothic in the Fiction of Carson McCullers

Mathematics and Natural Sciences

David Hugh Baldwin
Biology
Studies Into the Mechanism of Patterned Discharge by a Population of Motorneurons in the Barnacle Semibalanus Cariosus, *or How to Play Peek-and Poke with a Barnacle*

Alice Bennison (as of 6-18-85)
Biology
The Effects of Temperature on Cellular Aspects of the Humoral Response in the Newt; Notopthalmus Virideseens

Scott Betts
Biology
The Evolution of Metamorphic Patterns in Amphibian Populations

Richard A. Bradley Jr.
Chemistry
High Vacuum Ultraviolet Spectroscopy: Determining the Lower Barrier to Internal Rotation in Biphenyl

Aron Branscomb (as of 3-5-86)
Biology
Nuclear Introns: A Test of Two Mutation Protection Schemes and Historical Considerations

Christopher Miles Bruns
Biology
Protein Processing in the Bag Cells of Aplysia

Tiel T. Bryja
Biology
Control of Amphibian Metamorphosis: Food and Hormone Level Interaction

Robert E. Burney
Biology
Malaria: An Ever-increasing World Health Problem

John Colgrove
Chemistry
Studies of the Aldol Reactions of Some Cyclobutanone Enolates

Philippe Cuaz
Physics
A Fresh Look in the Cohesive Energy of Crystals

Clyde E. Cutting
Mathematics
The Internal Logic of a Topos

Hieu-Trang Thi Dang
Mathematics
Uniform Distribution

Jeanne Aletheia Elizabeth DeVoto (as of 11-19-85)
Mathematics
Shaken, Not Stirred: Some Algebraic Applications to the Theory of Error-Correcting Codes

Alexis Dimitriadis (as of 12-6-85)
Biology
Algorithms for Restriction Mapping

Christopher Roy Disdero
Physics
Circuitworks

Sheperd Samuel Doeleman
Physics
Geodesics: An Analytical and Computational Analysis

Elizabeth Exter (as of 5-15-86)
Physics
Three-two program, Applied Physics and Electronic Science

Constance Ann Fitzsimmons
Biology
Behavioral, Social and Morphological Characteristics in the Evolution of Monogamy and Polygamy Among Neotropical Primates

Eleanor Goodall (as of 12-17-85)
Biology
Immunocy to Chemical Localization of Estrogen Receptors During Estrogen-Induced Epithelial Cell Proliferation in the Neonatal Hamster

Timothy Gould (as of 6-28-85)
Physics
Three-two program, Applied Physics and Electronic Science

Michael Thomas Gregg
Biology
Immune Neuroendocrine Interaction in Xenopus Laevis, *The South African Clawed Toad*

Hans-Urs Gutman (as of 5-9-86)
Biology
MS and Stress

Anne Hamik
Biology
A Model for the Association Between Clathrin and Cell Surface Receptors in the Recycling Pathway

Christian Mathias Haugen
Chemistry
Stimulation and Inhibition of Phosphoribomutase

John Armand Haugen
Chemistry
Salt Bridges and Redox Mediators: Aspects of a Biochemical Fuel Cell

Maria Haws (as of 7-2-85)
Biology
Urban Stream Ecology: 4 Portland Streams

Reid Heimbeck (as of 9-17-85)
Physics
The Simple Inverted Pendulum with Variable Horizontal Support: A Study into the Construction of a Machine Model

Lisa Hess
Biology
Lymphocyte Homing During a Graft Versus Host Response in Xenopus

Ann Highet
Biology
The Basis for Compromised Suppression During Xenopus laevis *Metamorphosis*

Christina Johnson
Biology
Functional and Structural Characterization of Neurosecretory Granules

Kelly S. Kreitlow (as of 2-12-86)
Biology
Proanthocyanidins and Related Compounds in Leaves and Tissue Cultures of Flowering Currant (Ribes Sanquineum) *and Douglas Fir (Pseudotsuga Menziesii)*

Christopher King Langford (as of 4-28-86)
Biology
An Ultrastructual Examination of the Epithelial/Stromal Interface of the Glands of the Uterine Endometrium During Repair Phase of Induced Menstrual Cycles in Masca Fascicularis*–or–How I Stopped Worrying and Learned to Love Small Dark Rooms*

Loraine Michelle Lawlor
Biology
Neuroglial Cells: Transmitter Modulators in Epilepsy and Depression

Karen R. Lentfer
Biology
The Effects of Progesterone on Estrogen Receptors in the Endometrium of the Rhesus Macaque

Erik Leonard (as of 12-18-85)
Physics
When Does the Density of the States Foreshadow Phase Transitions?

Richard T. Ludwig
Chemistry
A Palladium Catalyzed [1, 3] *Sigmatropic Shift of a 1-Vinyl-1-Methoxy3Cyclobutane*

Bruce D. Malamud
Physics
Levitation by Light Pressure: An Experimental Thesis

Nicholas McPhee (as of 12-16-85)
Mathematics
The Relationship Between Deterministic Finite Automata and Two-Way Deterministic Finite Automata

Robert Miner
Mathematics
Methods of Factoring Univariate Polynomials

Gil J. Moskowitz
Biology
Interganglion Communicating Neurons in The Barnacle: Which Way Did They Go?

Kurt Randall Myers
Chemistry/Physics
A Relationship of a Trinity: A Linear Variational Approach to Calculate the Ground State Energy of Helium Using the Wave Functions from an Exactly Soluble Three-Body Model

Duy Tuan Nguyen
Chemistry
An Attempt at Asymmetric Induction Using the Paterno-Buchi Reaction Between (4S, 5S)-4, 5-Dimethyl-2-Methylene-1, 3-Dioxolane and Heptanal

Catherine Ann Nobis (as of 10-8-85)
Biology
Glucocorticoid Modulation of the Immune Response in the Anuran, Xenopus Laevis

Geneviève Hélène Nonet
Chemistry
Purification and Partial Kinetic Characterization of Human Orotate Phosphoribosyltransferase for the Potential Application to the Study of Substrate Analogs of Phosphoribosylpyrophosphate

Keith R. Packard
Mathematics
Rational Quadratic Forms

Tuan Quoc Pham
Biology
Inhibition of Regulatory T Cell Functions in Xenopus Laevis *Permanent Larvae*

Patrick Carnahan Phillips
Biology
Plasticity and Maternal Effects in Amphibian Early Development

Jonathan David Plant
Biology
Three-two program, Veterinary Medicine

Rebecca Lee Poulson
Biology
The Effects of Forest Management on Dendroctonus Pseudotsugae, The Douglas-Fir Beetle

Grace Y. Richter
Biology
A Molecular Genetic Approach to the Investigation of Nitrogen Metabolism in Candida albicans

Edmund Rhett Savage
Physics
Nonlocality

Paul Shaffer
Three-two program, Applied Physics and Electronic Science

Ketan Shaw
Three-two program, Applied Physics and Electronic Science

John Shannon
Three-two program, Applied Physics and Electronic Science

Thaddeus T. Shannon III
Mathematics
On Normality

Lawrence Scott Sherman
Biology
Production of Antibodies to Unique Antigens on the Surface of Neurofibroma Fibroblasts in vitro

Thomas R. Shieber
Physics
On the Structure of Solar Torsional Oscillations

Kevan Michael Shokat
Chemistry
Synthesis of a Precursor of PRCPCP, a Non-hydrolyzable Analog of Phosphoribosylpyrophosphate (PRPP)

Colin Andrew Smith
Chemistry
Novel Synthesis and Double Deprotonation of Methyl [2-(1, 3-Dithianyl)] Acetate

Ann Elizabeth Snell
Biology
Evidence of Oncogene-Related Sequences in the Genomic DNA of Neurospora

Horace Tso
Physics
An Investigation of Spectral Lines Overlapping and its Effect on Line Shifts

Sabir Wajihuddin (as of 1-16-86)
Mathematics
Properties and Representations of the Schwartz Function

Louisa Weix (as of 5-20-86)
Chemistry
Beta Ylide Anions of (1, 3-Dithian-2-ylmethyl) triphenylphosphonium Bromide and 2-Carboethoxyethyltriphenylphosphonium Bromide

Adam K. Whiting
Chemistry
High Voltage Electric Discharge as an Approach to the Gas Phase Absorption Spectrum of Wurster's Blue

Katherine L. Widdowson
Chemistry
Attempted Synthesis of the tris Ruthenium (2) 4,4′-Dimethyl 2,2′-Bipyrazinium Ion

Byron C. M. Williams
Biology
The Methylation Pattern of the Promoter and 5′-Regions of the Neurospora Crassa Ribosomal RNA Genes

Robert Bradley Wilson
Chemistry
Lost in the Continuum

Thomas Bachman Wilson
Biology
Some Aspects of the Water Economy and Bladder Capacity of Juvenile and Adult Mexican Leaf Frogs, Pachymedusa Dacnicolor: *A Significant Pee-Value?*

David Francis Wolczyk
Biology
The Existence of Repeated Sequences in the NTS Regions of the DNA of Neurospora Crassa: *An Open Question –or– An Attempt at Constructing a Cosmid Genomic Library*

Todd Carpenter Zankel
Chemistry
Investigation of Double Stereodifferentiation with Mutual Kinetic Resolution in the Wittig Reaction

Philosophy, Education, Religion, Psychology

Michael Baker (as of 2-7-86)
Psychology
To go or not to go, that is the question. Whether 'tis nobler in the mind . . . Biological Determination and the Nature of Intelligence in the Selected Works of Stephen Jay Gould and Arthur Jensen

Zeff Bjerken
Religion
God's Relationship to Man in the Neoclassical Theology of Charles Hartshorne

Leda Margaret Black
Philosophy/Religion
How to Relate to Things With Words: Martin Buber's Philosophy of Language

Andrew J. Blum
Philosophy
Throwing Stones: A Rap About Nuclear Warfighting Strategy

Brett A. Bodayla
Psychology
Effects of In-Store Background Music on Customer Behavior: Manipulation of Volume and Tempo

Anne S. Bothner-By (as of 1-6-86)
Religion
The Role of "The Gospel of Thomas" in the Development of Early Christianity

William Blackburn Douglas
Religion
The Unexamined Is: A Reading of Platonic Ontology

Frederick Arthur Dushin
Philosophy/Religion
Toward an Ethnography of Furniture

Peter Elias (as of 2-19-86)
Psychology
Symbolic Interaction, Attribution and Situated Identity: Making the Social Science of Interpersonal Cognition, Social and Science

Michael Eugene Foat
Religion
Who Shall Declare His Generation? The Arian Controversy of the Early Fourth Century

Steve Luck
Psychology
The Effects of Attention, Task-Relevance, and Sequence Variability on Cognitive Event-Related Brain Potentials

Anne Elizabeth Magruder
Religion
Falwell's Crusade: The Tradition of Reform in American Evangelicalism

Madeleine R. Martindale
Psychology
Subjective Time Estimations of Short Intervals in Retrospect: I-E Locus of Control Beliefs and the Time Order Effect

Evin Morris (as of 4-10-86)
Philosophy
Philosophizing Outside the Gates of Eden; Habermas' Theory of Cognitive Interests

Mark Gregory Oakes
Philosophy
The Metaphysics of Value in Nietzsche

Eric Todd Olson
Philosophy
Three Theories of Proper Names

Deborah Rabin (as of 1-20-86)
Psychology
An Exploration of Human Intelligence

Miriam R. Sherer
Philosophy
David Hume: Economist and Philosopher

Joshua Shabtai Skolnik
Psychology
Expert Testimony and Judicial Commentary on Eyewitness Testimony: Differential Effects on Mock Juries

Stephanie Stevens
Religion
All My Relations: Theology of a Natural Order in the Work of Mary Daly and Alfred North Whitehead

Alan T. L. Sun
Religion
The Transmission of Authority in the New Testament

Jef Vivian
Psychology
Nonexponentiality in Photopic Dark Adaptation: A Theory of Threshold Detection

Theodore H. Wang
Psychology
Inducing Behavior Change Through Commitment: A Review and Two Group Recycling Experiments

Karen Carolyn Wilson
Psychology
Sex Role Orientation and Locus of Control as Predictors of Life Satisfaction

Nathan James Wilson
Psychology
Standards for Deviation: Tools for Reinforcing Variability

Matthew Thomas Witt (as of 9-27-85)
Psychology
The Effects of Status Perceptions on Helping Behavior

Interdivisional Majors

Dina Alkassim
History/Literature
Disfiguring the Anecdote: A Study in Interdisciplinary Politics

Jonathan P. Bay (as of 5-24-85)
History/Literature
Poetry as Identity: Edward Taylor's Determined Course Through an American Wilderness

Sarah Buff
History/Theatre
Douglas Sirk and George Stevens Present the American Family in the 1950's

Keven de la Cruz
Philosophy/Mathematics
The Philosophical Implications of Closed Timeline Curves

Ellen Mitsue Eades
History/Literature
Maids, Mothers, and Margery Kempe: Women of Religion in the Middle Ages

Paul S. Hempel
Economics/Mathematics
The Nonparametric Analysis of Cost Minimizing Behavior: An Examination of Three Generating Public Utilities

Michael Brian Hoberman
American Studies
Loomings: Herman Melville's Crafting of the American Long Bow

Steven Jay Hooker
Literature/Theatre
Southern Tennessee

Ahsan Jamil
Economics/Mathematics
Pakistan's Education Sector: Planning and Implementation Problems

Evan Stuart Rose
International Studies
Babylon Makes the Rules: Inequality, Ideology, and the Perpetuation of the Status Quo in Jamaica

Michitaka Soga
International Studies
Japan Rearmed

Tasha Spencer
Classics/Religion
The Likelihood of Plato's Likely Account: A Reading of Plato's Timeaus

John M. Trombold
History/Literature
The Formal Politics of Paterson

Wayne Turner
Literature/Theatre
The Transparent Mask–Representation in the Theatre of Robert Wilson

Sheldon P. Yett
International Studies
Feeding the Full and Starving the Hungry: The Use of Food Aid as a Foreign Policy Tool

Master of Arts in Liberal Studies

Lynette Crane
English Literature
The Prism–A Collection of Short Stories

Ursula Harvey (as of 12-18-85)
General Literature
Weimar: Politics and Literature

David William Kniefel
Political Science
Political Factors Influencing the Ferrous Scrap Industry of the Pacific Northwest

Pamela Herrmann Miles
Psychology
Single Dose Lithium Omissions

Jan Powell
Theatre
Alien Beauty: An Analysis of the Play The Tempest, or the Enchanted Island *by John Dryden and Sir William Davenant (1670)*

Reed College
Portland, Oregon 97202

Reed College, South Africa, and the U.S. Military

A recent federal law (the Solomon Amendment) links federal financial aid to draft registration. This law has the effect of imposing a political test on who will be a student at Reed. Already, students with religious or political objections to draft registration have been forced to drop out of school or take a leave of absence. Faculty and students alike believe that this law has a damaging effect on the academic freedom and political diversity of the college. Nonetheless, the Reed administration has refused to take any official action to mitigate the effects of the Solomon Amendment by providing some form of alternative aid.

During this week of Reed's graduation ceremony, the government of South Africa carried out bombing raids against several other African nations. This week, the total death toll from two years of government action against the anti-apartheid movement in South Africa surpassed sixteen hundred. South African Prime Minister P.W. Botha promised that the latest wave of government violence was only "the first installment." (Oregonian, 5/22)

The international community has called for economic sanctions against the brutal South African regime. However, despite worldwide calls for divestment, a substantial portion of Reed's endowment remains invested in companies doing business in South Africa.

At graduation, students, alumni and friends of Reed can help Reed students gain a greater voice in college affairs. Our current goals are full divestment of college money from South Africa and the establishment of an alternative aid program for students who refuse to register for the draft. *Mention these issues in all your contacts with members of the Reed faculty and administration.* Join our call for divestment! And when you are solicited for donations from the college, respond with your own questions and requests. What role do current students play in the governance of the college? What is the Reed Institute doing to combat racism and militarism? When will it take action on the Solomon Amendment and divestment?!